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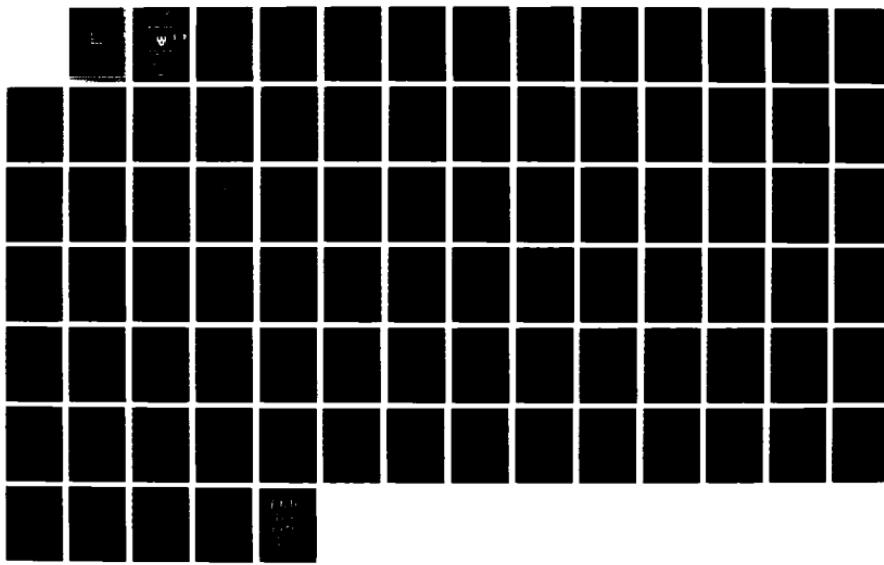
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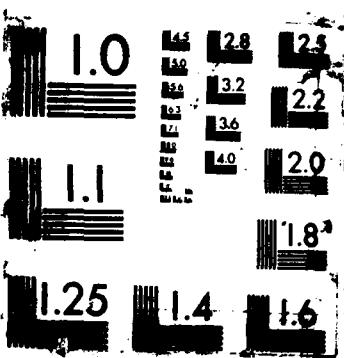
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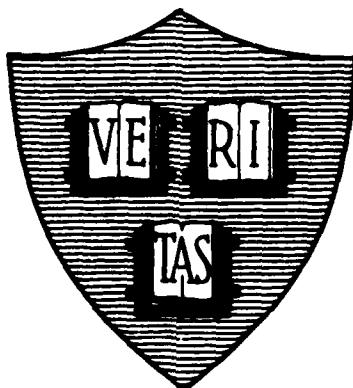
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An annual report of the JSEP (Joint Services Electronics Program) in solid state electronics, quantum electronics, information electronics, control and optimization, and electromagnetic phenomena is presented. Results of the research to date are summarized and significant accomplishments are discussed.		

Joint Services Electronics Program

N00014-84-K-0465

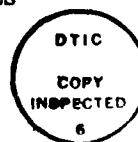
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INTRODUCTION

Because of a shift in the funding cycle, this report covers progress made during only the first nine months of calender year 1987 in the work of the eleven Research Units funded under the Joint Services Electronics Program at Harvard University. It is broken down into four major divisions of electronic research: *Solid state electronics, quantum electronics, information electronics, and electromagnetic phenomena*. Following the report of the work of each Unit, there is a complete annual report of the associated Publications/Patents/Presentations/Honors. This report also includes a section on *Significant Accomplishments* which contains selected highlights from several of these areas. These are "From the Semiclassical to the Quantum Regime in the Josephson Effect" by Research Unit 4, "Perturbation Analysis (PA) of Discrete Event Dynamic Systems (DEDS)" by Research Unit 10, and "Lateral Electromagnetic Pulses" by Research Unit 11.

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I. SOLID STATE ELECTRONICS

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Dr. B. Ocko	Mr. Y. M. Li
Dr. H. Rogalla	Mr. I. Tidswell
Mr. K. Babcock	Mr. W. A. Turner
Mr. B. F. Bateman	

I.1 Electronic and Magnetic Properties of Diluted Magnetic Semiconductors (DMS). H. Ehrenreich, K. C. Hass, and B. Larson, Contract N00014-84-K-0465; Research Unit 1.

A common theoretical framework describing the electronic structure and magnetic interaction in Mn-alloyed II-VI diluted magnetic semiconductors (DMS) has been developed. This framework relates the hierarchy of electronic and magnetic interactions on energy scales ranging from 10^{-5} eV to 10 eV. It contains empirical electronic parameters obtained from a variety of data and obtains an internally consistent microscopically-based physical picture. With this input it is possible to calculate the magnetic properties from first principles [1]-[5].

We have considered compounds of the form $(\text{II})_{1-x}\text{Mn}_x(\text{VI})$ for a variety of ingredients belonging to Groups II and VI of the periodic table. Among the former we have considered Cd, Zn, and Hg, and for the latter Te, Se, and S.

The calculation of the exchange constants draws on theoretical concepts developed for insulating antiferromagnets. These were developed in the early 60's by Anderson, Moriya, and others. However, this is the first time that both isotropic or conventional superexchange interactions among Mn ions and anisotropic interactions characterized by the dominant Dzyaloshinsky-Moriya interaction have been treated on a unified footing [6]. The anisotropic part arises as a result of spin-orbit interactions and amounts to only about 5% of the total exchange interaction. However, it is the dominant mechanism determining the linewidth of EPR spectra; these are reasonably explained by the present calculations. The calculated exchange constants themselves are within 20% of the measured values. This work thus represents the most accurate theoretical determination of exchange constants performed to date.

The significance of this work is due, first to the fact that DMS have practical promise as infrared detectors and magneto-optic devices because of their large Faraday rotation. They may be useful as sensitive magnetic field detectors, optical switches, modulators, and isolators. Second, these materials represent excellent model systems for the study of spin glasses and cluster antiferromagnets. Instead of reliance on model Hamiltonians having phenomenological coupling constants, it is now possible, with the present microscopic theory, to examine exotic magnetic phases in far greater detail than heretofore.

This work will be completed during the course of the next few months [6].

References:

1. K. C. Hass, B. E. Larson, H. Ehrenreich, and A. E. Carlsson, "Magnetic Interactions in Diluted Magnetic Semiconductors," *J. Magnetism and Magnetic Materials* **54-57**, 1283 (1986).
2. K. C. Hass and H. Ehrenreich, "Band Structure of Semimagnetic Compounds," Proc. XVI Int. School on the Physics of Semiconducting Compounds, 1987, *Acta Physica Polonica*, to be published.

3. B. E. Larson, K. C. Hass, H. Ehrenreich, and A. E. Carlsson, "Theory of Exchange Interactions and Chemical Trends in Diluted Magnetic Semiconductors," *Phys. Rev. B*, to be published.
4. H. Ehrenreich, K. C. Hass, B. E. Larson, and N. F. Johnson, "Electronic Theory of Mn-Alloyed Diluted Magnetic Semiconductors," Proc. of the Materials Research Society Symposium on Diluted Magnetic Semiconductors (J. K. Furdyna, R. L. Aggarwal, and S. von Molnar, Eds.), Boston, December, 1986, MRS, 1987, to be published.
5. H. Ehrenreich, K. C. Hass, N. F. Johnson, B. E. Larson, and R. J. Lempert, "Electronic Structure and Magnetic Interactions in Diluted Magnetic Semiconductors," Proc. of the 18th Int. Conf. on Physics of Semiconductors, (D. Engstrom, Ed.), 1986, World Scientific Publishers Co. (Singapore, 1987).
6. B. E. Larson, Ph.D. Thesis, Harvard University, 1987.

I.2 Superlattices. H. Ehrenreich, N. F. Johnson, and K. C. Hass, Contract N00014-84-K-0465; Research Unit 1.

Of the various candidate materials for infrared detectors, HgTe/CdTe superlattices are particularly important. Whether these devices are best fabricated from alloys or superlattices is still controversial. In order to provide some guidance to the prevailing thinking, we have undertaken a program to study the electronic and optical properties of superlattices to supplement that, carried out over the past few years, which is focused on alloys.

Superlattices have the advantage that they are periodic structures and as such have many of the theoretical properties to be expected of periodic lattices. In that context we have developed the *f*-sum rule for superlattices and related parameters such as band energies, momentum matrix elements, and effective masses to the properties of the constituent bulk materials. Applications thus far have been made to AlGaAs/GaAs and HgTe/CdTe superlattices [1],[2]. The effective masses both longitudinal and perpendicular to the growth direction have been obtained using a generalized Kane model. The results have been compared to experiment insofar as is possible. For the III-V system especially, which has been studied most extensively, the agreement is excellent. In the case of the II-VI system only the parallel masses have been determined

experimentally. Again the agreement is within the experimental error. It should be emphasized however that these calculations rely on the assumption of zero valence band offset. A relaxation of that assumption spoils the agreement with experiment. In particular, a band offset of 0.35 eV between the valence band edges in CdTe and HgTe, which is suggested by recent photoemission experiments, would yield completely unsatisfactory predictions. Since $k \cdot p$ perturbation theory has been very successful in predicting effective masses for bulk materials and since the present theoretical framework explains the III-V data satisfactorily, the discrepancy between cyclotron resonance and photoemission data represents a real dilemma, particularly since both experiments have been performed in the laboratory of J. P. Faurie. An understanding of band offsets is of obvious importance for device applications involving superlattices.

This theoretical work is being continued with emphasis now focusing on optical properties which are of importance in photoluminescence. Light-emitting materials in the visible, for example, in ZnTe/ZnSe may turn out to be practically important. The incentives for developing these devices are clarified if band offsets, exciton effects, and the strength of the optical matrix component are better understood. These matters are currently under investigation as both an application and a follow-on to the work on the *f*-sum rule.

References:

1. N. F. Johnson, H. Ehrenreich, K. C. Hass, and T. C. McGill, "f-Sum Rule and Effective Masses in Superlattices," *Phys. Rev. Letters*, to be published.
2. N. F. Johnson, H. Ehrenreich, and K. C. Hass, "Effective Masses and Optical Matrix Elements in Semiconductor Superlattices," *Superlattices and Microstructures*, to be published.

I.3 Superconductivity. H. Ehrenreich and K. C. Hass, Contract N00014-84-K-0465; Research Unit 1.

Opportunities for research and applications in this rapidly growing field are currently being explored. A model for the occurrence of high temperature superconductivity in $\text{YBa}_2\text{Cu}_3\text{O}_7$ has been constructed and preliminary estimates for both the transition temperature and the coherence length have been obtained. The model is based on plane-chain superexchange coupling. Its implementation makes use of the experience obtained in our extensive treatment of the magnetic properties of DMS. This work is being carried on in collaboration with K. C. Hass who has now left Harvard to join the Research Laboratory of the Ford Motor Co.

I.4 Electronic Theory for Materials Science. H. Ehrenreich, Contract N00014-84-K-0465; Research Unit 1.

An appreciable portion of Ehrenreich's proposed research effort during the past year has been devoted to a paper that has been published under the above title for a special materials science issue of *Science* [1]. It presents a general overview of the field as viewed by theorists. JSEP is explicitly acknowledged for supporting this work.

References:

1. H. Ehrenreich, "Electronic Theory for Materials Science," *Science* **235**, 1029 (1987).

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

K. C. Hass and H. Ehrenreich, "Band Structure of Semimagnetic Compounds," Proc. XVI Int. School on the Physics of Semiconducting Compounds, 1987, *Acta Physica Polonica*.

B. E. Larson, K. C. Hass, H. Ehrenreich, and A. E. Carlsson, "Theory of Exchange Interactions and Chemical Trends in Diluted Magnetic Semiconductors," *Phys. Rev. B*.

H. Ehrenreich, K. C. Hass, B. E. Larson, and N. F. Johnson, "Electronic Theory of Mn-Alloyed Diluted Magnetic Semiconductors," Proc. of the Materials Research Society Symposium on Diluted Magnetic Semiconductors (J. K. Furdyna, R. L. Aggarwal, and S. von Molnar, Eds.), Boston, December, 1986, MRS, 1987.

N. F. Johnson, H. Ehrenreich, K. C. Hass, and T. C. McGill, "f-Sum Rule and Effective Masses in Superlattices," *Phys. Rev. Letters*.

N. F. Johnson, H. Ehrenreich, and K. C. Hass, "Effective Masses and Optical Matrix Elements in Semiconductor Superlattices," *Superlattices and Microstructures*.

b. Papers Published in Refereed Journals

K. C. Hass, B. E. Larson, H. Ehrenreich, and A. E. Carlsson, "Magnetic Interactions in Diluted Magnetic Semiconductors," *J. Magnetism and Magnetic Materials* **54-57**, 1283 (1986).

H. Ehrenreich and T. C. McGill, "U.S. Electronic Materials Competitiveness: The Crisis and Proposed Resolutions," *DARPA Materials Research Council Report*, 1986.

H. Ehrenreich, "Electronic Theory for Materials Science," *Science* **235**, 1029 (1987).

R. J. Lempert, K. C. Hass, and H. Ehrenreich, "Molecular Coherent-Potential Approximation for Zincblende Pseudobinary Alloys," *Phys. Rev. B* **36**, 1111 (1987).

H. Ehrenreich, K. C. Hass, N. F. Johnson, B. E. Larson, and R. J. Lempert, "Electronic Structure and Magnetic Interactions in Diluted Magnetic Semiconductors," Proc. of the 18th Int. Conf. on Physics of Semiconductors (D. Engstrom, Ed.), 1986, World Scientific Publishers Co. (Singapore, 1987).

K. C. Hass and D. Vanderbilt, "Structural Properties of II-VI Crystals and Alloys," Proc. of the 18th Conf. on Physics of Semiconductors (D. Engstrom, Ed.), 1986, World Scientific Publishers Co. (Singapore, 1987).

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

Note: A number of presentations, most of them invited, have been made at major conferences by both H. Ehrenreich and K. C. Hass during the past year. These presentations, many of which have also given rise to publications that are duly cited, are the following:

“Electronic Theory of Mn-Alloyed Diluted Magnetic Semiconductors,” Materials Research Society Meeting, Boston, MA December, 1986.

“Electronic Structure and Magnetic Interactions in Diluted Magnetic Semiconductors,” 18th Int. Conf. on the Physics of Semiconductors, Stockholm, Sweden, August 11-15, 1986.

“Structural Properties of II-VI Crystals and Alloys,” 18th Int. Conf. on the Physics of Semiconductors, Stockholm, Sweden, August 11-15, 1986.

“Bond Relaxation in $Hg_{1-x}Cd_xTe$ and Related Alloys,” 1986 Workshop on the Physics and Chemistry of Mercury Cadmium Telluride, Dallas, TX, October 7-9, 1986.

“Theory of the Electronic Structure and Magnetic Interactions in Mn-Based Diluted Magnetic Semiconductors,” March Meeting of the American Physical Society, New York, NY, March 16-20, 1987.

“Band Structures of Semimagnetic Compounds,” XVI Int. School on the Physics of Semiconducting Compounds, Jaszowiec, Poland, April 6-12, 1987.

“Electronic and Magnetic Properties of II-VI Diluted Magnetic Semiconductors,” Third Int. Conf. on II-VI Compounds, Monterey, CA, July 12-17, 1987.

“Effective Masses and Optical Matrix Elements in Semiconductor Superlattices,” Third Int. Conf. on Superlattices, Microstructures and Microdevices, Chicago, IL, August 17-20, 1987.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1987.

Dr. K. C. Hass, Mr. N. F. Johnson, and Mr. B. Larson.

I.5 Investigation of Amorphous Hydrogenated and Fluorinated Alloys of Silicon and Germanium. B. F. Bateman, J. H. Burnett, J. R. Eggert, S. J. Jones, Y. M. Li, K. D. Mackenzie, W. A. Turner, and W. Paul, Contracts N00014-84-K-0465 and SERI Subcontract XB-7-06071-1-1; Research Unit 2.

We have continued our investigation of the reasons for the deterioration in photoresponse of amorphous hydrogenated silicon-germanium alloys ($a\text{-Si}_{1-x}\text{Ge}_x\text{:H}$) compared with that of amorphous hydrogenated silicon ($a\text{-Si:H}$), and the reasons for the partial restoration of the photoresponse when the preparation plasma is the mixture ($\text{SiF}_4 + \text{GeF}_4 + \text{H}_2$) instead of the usual ($\text{SiH}_4 + \text{GeH}_4$) [1]. Our efforts during the past year have concerned (1) continued measurement, by time-of-flight (TOF) techniques, of the mobility-lifetime products in the above-mentioned series of alloys [2], (2) collaboration with the group of Dr. M.-L. Theye at the Laboratoire d'Optique in Paris, to examine the sub-band-gap absorption spectra of intrinsic, P-doped, B-doped and (P,B) compensated $a\text{-Si:H}$ films, both by the method of photothermal deflection spectroscopy (PDS) and by the variation of photoconductivity techniques called the constant photocurrent method (CPM) [3], (3) collaboration with the group of Professor R. E. Norberg at Washington University, St. Louis, to produce deuterated amorphous silicon-germanium alloys for examination by deuteron quadrupole resonance, (4) collaboration with the group of Professor Gerald Lucovsky at North Carolina State University, to examine the evolution spectra and differential scanning calorimetric spectra of NCSU's magnetron-sputtered $a\text{-Si:H}$ and magnetron-sputtered $a\text{-Si}_{1-x}\text{Ge}_x\text{:H}$, and also of their remote-plasma-chemical-vapor-deposited amorphous semiconductors, (5) collaboration with the Naval Research Laboratory, in the provision of samples (by us) for their measurements of photoluminescence effects, (6) development of a system to produce amorphous and crystalline semiconductor thin films and multilayers, by photochemical vapor deposition, and (7) completion of our experimental and theoretical studies of midgap injection-induced absorption in $a\text{-Si:H}$.

and its relation to the gap density of states and recombination [4]. In this report, we concentrate on items (1) and (2) only.

The product of (quantum efficiency) \times (mobility) \times (lifetime) or $(\eta\mu\tau)$ for electrons in semiconductors, derivable from measurements of the d.c. photocurrent, may be shown to be proportional to $(F_0\alpha)^{\gamma-1}$, where F_0 is the density of photons/cm²-s used for the measurement, α is the absorption coefficient, and γ is the empirical coefficient conventionally used to describe the photon intensity dependence of the photocurrent, which is $i \propto (F_0\alpha)^\gamma$. Much work in the literature seems to ignore this dependence of $(\eta\mu\tau)$ on absorbed photon flux. The present formulation has been used to carry out a quantitative comparison of the $(\eta\mu\tau)$ products vs. x for hydride- and fluoride-produced samples, after careful corrections for surface effects and created carrier densities. The result is, as reported earlier, that the $(\eta\mu\tau)$ products decrease rapidly and monotonically with x .

The $(\mu\tau)$ products determined by TOF techniques measure the bulk properties of sandwich-type structures. However, as shown in Figure I.1, these $(\mu\tau)$ products are about two orders of magnitude lower than those found from the d.c. photoconductivity measurements. The reason proposed by us (and independently by E. A. Schiff of Syracuse University) is that the τ 's involved are very different: that in the TOF experiment is the time for first deep trapping, which eliminates the photocarrier "permanently" from the TOF experiments, whose duration is of the order of microseconds; the τ in the d.c. photoconductivity experiment is the 100 times longer time until the photocarrier recombines after many releases into the extended states from the deep traps. This explanation removes a long-standing anomaly which has apparently eluded earlier explanation.

The second notable element shown in Figure I.1 is that the $\mu\tau$ products for electrons in hydride- and fluoride-derived material are the same, in contrast to the relative $(\eta\mu\tau)$'s from photoconductivity experiments. This is not presently understood,

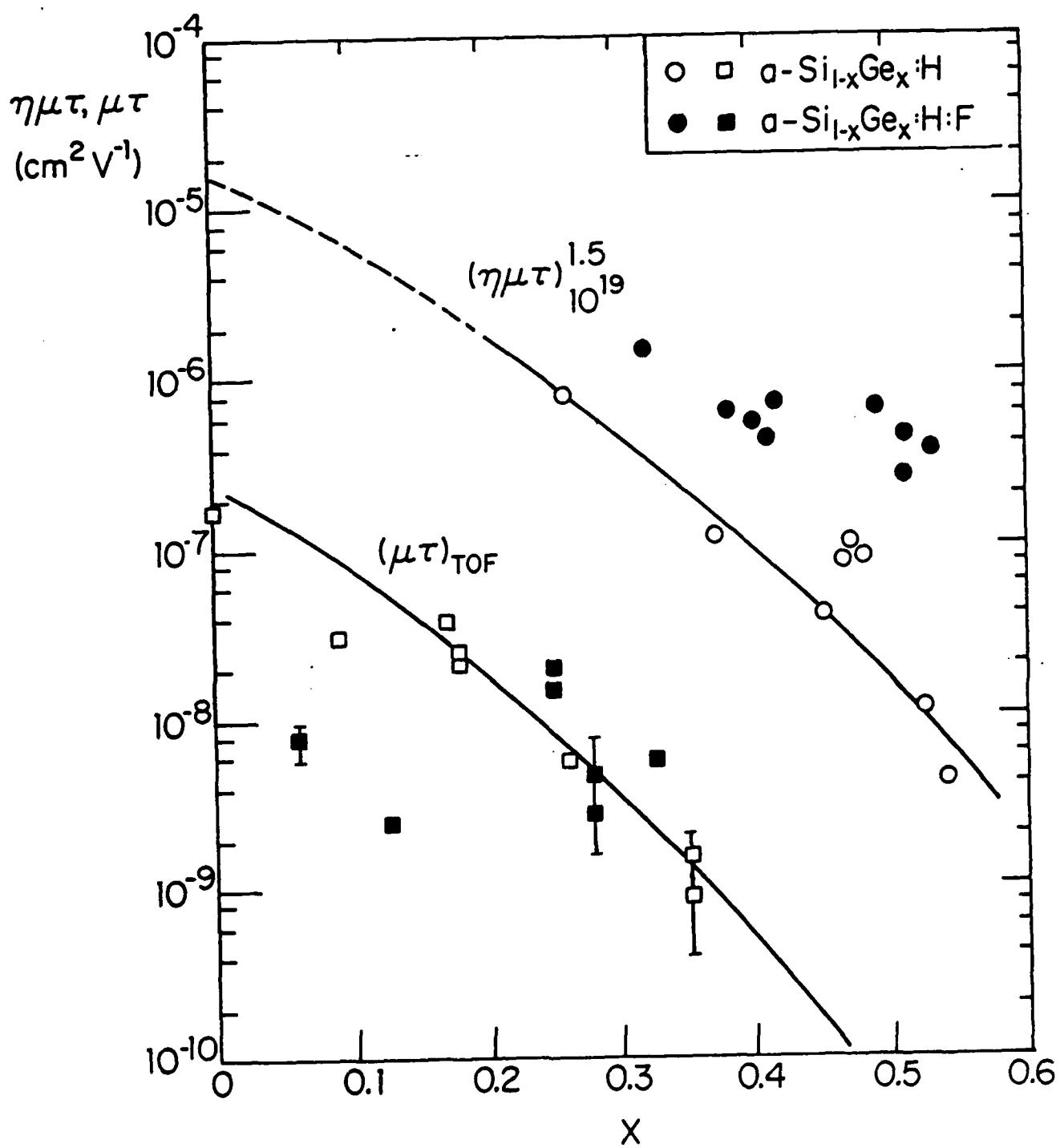


Figure 1.1. Variation of normalized $\eta\mu\tau$ product from photoconductivity and $\mu\tau$ product from time-of-flight with x .

but clearly, any model for the improved photoconductivity must include this element. The improved photoconductivity of the fluoride-derived material may be explained by two possible models:

- (1) a longer recombination time, produced by a difference in the gap density-of-states. This model faces the potential difficulty that the measurements we have so far done to identify this difference (space-charge-limited currents, photoluminescence intensity, sub-band-gap absorption) have not revealed any significant change in the density-of-states. It also must explain away the difficulty that the $(\mu\tau)$ products from TOF are the same for the hydride- and fluoride-derived samples.
- (2) a structure with two transport paths, one of high mobility, the other of low mobility, with either one possibly dominant in dark transport, but with the higher mobility path dominant in photo-transport. This kind of model fits the observations from transmission electron microscopy, gas evolution and oxygen uptake that the microstructures of films produced from $(\text{SiH}_4 + \text{GeH}_4)$ and $(\text{SiF}_4 + \text{GeF}_4 + \text{H}_2)$ are distinctly different.

The second investigation on which we have spent much effort is an important one in all thin-film physics: the accurate determination of absorption coefficients of the order of 10^{-2} cm^{-1} and upwards in films only microns (10^{-4} cm) thick. The usual measurements by transmission and reflection are not usable in this domain of (αt) products. Our work has been directed at deducing the absorption spectrum by the CPM (Harvard) and by PDS (Paris) on samples prepared by us. To date, we have established that:

- (1) The PDS method is very sensitive to surface states and surface band-bending, so that only measurements on relatively thick (say, $> 3 \mu\text{m}$) samples reflect the properties of the bulk,

- (2) the PDS spectrum below the absorption edge of the semiconductor may be dominated by localized state-to-localized state transitions,
- (3) the CPM spectrum is sensitive to the creation by illumination of metastable defects,
- (4) the CPM spectrum is more reflective than the PDS of the bulk properties, and
- (5) there are distinct differences between the PDS and CPM spectra which depend on the sample preparation and on the position of the Fermi level.

References:

1. K. D. Mackenzie and W. Paul, Spring 1987 Meeting of the Materials Research Society, to be published.
K. D. Mackenzie and W. Paul, Sub-Contractors Meeting of the Solar Energy Research Institute, January 1987.
K. D. Mackenzie, J. H. Burnett, J. R. Eggert, Y. M. Li, and W. Paul, paper presented at the International Conference on *Amorphous Semiconductors*, Prague, August 1987, to be published in *J. Non-Cryst. Solids*.
2. K. D. Mackenzie and W. Paul, manuscript in preparation.
K. D. Mackenzie and W. Paul, paper presented at the International Conference on *Amorphous Semiconductors*, Prague, August 1987, to be published in *J. Non-Cryst. Solids*.
3. L. Chahed, G. Vuye, M.-L. Theye, Y. M. Li, K. D. Mackenzie, and W. Paul, paper presented at the International Conference on *Amorphous Semiconductors*, Prague, August 1987, to be published in *J. Non-Cryst. Solids*.
4. J. R. Eggert and W. Paul, *Phys. Rev. B* 35, 7993 (1987).
J. R. Eggert and W. Paul, submitted to *Phys. Rev. B*.

I.6 Pressure Dependence of Excitation Photo-Luminescence in $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ Multi-Quantum Wells. J. H. Burnett and W. Paul, Contracts N00014-86-K-0744 and N00014-84-K-0465; Research Unit 2.

Multi-quantum wells and superlattices of group 3-group 5 compounds such as GaAs are important semiconductors having both great fundamental interest and de-

vice importance. We have chosen to study the pressure dependence of suitable optical spectra of such structures as a way to elucidate the fundamental mechanisms of quantized state formation and of tunneling between adjacent wells. The philosophy of this approach is that the pressure dependence of the band structures of both well and barrier are well-known, so that a pressure experiment can study the result of varying the band structures in a known way on a single structure.

Specifically, we have investigated the excitation photo-luminescence (EPL) spectra of several $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ multi-quantum wells (MQW) as a function of pressure and temperature. The effect of pressure on the band structure of the well (GaAs) and barrier ($\text{Al}_x\text{Ga}_{1-x}\text{As}$) layers is well established, and we are able to sort out the quantized electron and hole energy levels from the EPL spectra, so that we can make a direct study of the electron and hole energy levels as a function of the band structure of the well and barrier layers. We have chosen structures consisting of pairs of quantum wells with barrier widths allowing coupling of the confined states. Single coupling between pairs was chosen to simplify the analysis, but the results should be extendable to the multiple coupling in superlattices.

For $x = 0.3$ and pressure (P) < 40 kbar, the principal effect of pressure is to change the nature of the barrier, specifically to alter the relative energies of the Γ and X minima. (This effect is similar to the change in relative energies of the two minima when x is changed at atmospheric pressure.) The coupling between wells through the barrier is expected to depend on the relative energies of Γ and X (the well electrons have predominantly Γ symmetry), especially in the range of pressure where the energy of X is below that of Γ ($P > 10$ kbar). Thus we have focused our study on the behavior of the QW levels as a function of the relative energies of Γ and X for $10 < P < 40$ kbar.

In collaboration with Dr. Emil Koteles of GTE Corporation, we have designed three MQW structures which were produced by MBE at GTE Laboratories.

- (1) (*Uncoupled*) GaAs/Al_{0.3}Ga_{0.7}As MQW's with barrier widths of 150 Å (well widths \sim 200 Å). Calculations predict that the wells are completely uncoupled at atmospheric pressure.
- (2) (*Slightly coupled*) GaAs/Al_{0.3}Ga_{0.7}As double QW's with barrier widths of 70 Å (well widths \sim 100 Å). Calculations predict that the splitting of the electron energy levels due to coupling should be of the order of the experimental line widths.
- (3) (*Strongly coupled*) GaAs/Al_{0.3}Ga_{0.7}As double QW's with barrier widths of 30 Å (well widths \sim 100 Å). Calculations predict that the splitting of the electron energy levels due to coupling should be much larger than the line widths.

We have completed measurements of excitation photoluminescence of sample (1) for pressures of 0–34 kbar. For P = 1 bar (Γ = 5 K and 77 K) the energy levels of the system are consistent with no coupling. The EPL spectra (77 K) is unchanged (except for a rigid shift up in energy) for P up to 34 kbar, except that the peak assumed to correspond to the $1e - 3hh$ transition has a marked change in relative position and intensity at P = 29 kbar. This pressure is near that at which the barrier X crosses over the well Γ . We do not know yet why only this one transition is affected, but we expect that measurements on other samples will give us clues.

The EPL spectra of sample (2) at P = 1 kbar (T = 5 K) shows no evidence of coupling except for possibly some broadening of the peaks. We are now measuring the EPL spectra of this sample as a function of pressure and temperature. The EPL spectra of sample (3) at P = 1 bar (T = 5 K) is very different from samples (1) or (2), which we attribute to strong coupling between the wells. We will next measure this sample as a function of pressure and temperature.

After completing the measurements and analyses of these samples we hope to extend this investigation to quantum-well structures with multiple coupling, i.e., su-

perlattices. We expect that this investigation will contribute to the understanding of the nature of the electron and hole states (sub-bands) in GaAs/GaAlAs superlattices, and in particular clarify the role of the X-minima.

I.7 Metastable Semiconducting Alloys of $Ge_{1-x}Sn_x$. S. Lee and W. Paul, Contract N00014-84-K-0465; Research Unit 2.

In previous reports we have discussed the production, by R.F. sputtering of composite crystalline targets, of films of amorphous $Ge_{1-x}Sn_x$ with x determined to be between 0 and 0.4 by electron microprobe examination. When this material was heated in a differential scanning calorimeter, it showed two peaks postulated to be caused by crystallization and phase separation, respectively. The temperature interval between the two peaks (~ 10 K) and their width on the temperature scale (~ 7 K) was such as to make it difficult to crystallize the material without causing some phase separation involving β -Sn.

During this report period we have succeeded in producing crystalline films of $Ge_{0.77}Sn_{0.23}$ without any phase-separated β -Sn mixed in, as judged by diffraction patterns of sharp rings measured in a Phillips 420 scanning electron microscope. In transmission, the grain growth looks very uniform and is of the order of 100–400 Å. This result was made possible by a series of trials of different deposition conditions which eventually yielded material giving two DSC peaks of FWHM ~ 7 K but separated by ~ 20 K instead of ~ 10 K.

From the ring diffraction pattern we found the lattice constant of the crystallized alloy, and, assuming Vegard's Law to hold, deduced a Sn concentration of $23 \pm 2\%$. Through the use of X-ray analysis on the STEM we deduced the Sn concentration to be $23 \pm 1\%$ over the complete TEM grid, in satisfactory agreement with the inference from the diffraction pattern, and evidently verifying the appropriate assumption of Vegard's Law. X-ray analysis on the STEM of the material in its as-deposited, amorphous state

gave an Sn concentration of $23 \pm 0.5\%$. The uniformity of the Sn concentration over the area of the TEM grid was checked and found to be satisfactory to within 0.5%. The agreement of the Sn concentration in the amorphous film with the percentage of Sn in the crystallized alloy serves as a further demonstration, if any were needed, that the phase separation is below detectable values.

Although the separation of the two DSC peaks (~ 20 K) was sufficiently large to permit us to make a crystallized alloy without phase separation, we did carry out some experiments to determine whether preparation conditions could be further varied so as to increase the separation of the peaks and/or to make them narrower. These attempts did not lead to much improvement in the peak separation or peak widths.

We have concentrated on the use of a composite target yielding crystalline $Ge_{0.77}Sn_{0.23}$ and have been able to make films reproducibly, with the same DSC signature, and the same TEM results on crystallization.

We used films deposited on Corning 7059 glass from the successful deposition runs discussed above to determine the optical absorption spectra in both the amorphous and crystallized states. We found an optical gap of 0.45 ± 0.01 eV in both the amorphous and crystalline states. This gap is smaller by about 0.1 eV from that expected from a linear interpolation of the band structure of the Ge and α -Sn end points.

Future work will concentrate on confirmation and extension of these optical spectra and study of amorphous and crystallized alloys of different x .

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

J. R. Eggert and W. Paul, "Recombination in Disordered Semiconductors: The Nearest Available Neighbor Distribution," *Physical Review*.

b. Papers Published in Refereed Journals

J. R. Eggert and W. Paul, "Mid-Gap Injection-Induced Absorption in Amorphous Silicon," *Phys. Rev. B* 35, 7993 (1987).

Note: In addition, the group produced six other publications on related work supported primarily by other contracts, with subsidiary support from the JSEP.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1987.

Dr. K. D. Mackenzie, Mr. B. F. Bateman, Mr. G. H. Burnett, Mr. J. R. Eggert, Mr. S. J. Jones, Mr. S. Lee, Mr. Y. M. Li, and Mr. W. A. Turner.

I.8 X-Ray Reflection Characterization of Solid Surfaces. B. Ocko, I. Tidswell, and P. S. Pershan, Contracts N00014-84-K-0465, NSF DMR-85-13523, and NSF DMR-86-14003; Research Unit 3.

In the last year we have continued our investigation of X-ray reflection from silicon surfaces using the Harvard MRL Rotating Anode X-Ray Source (RAXS) and on the X22-B beam line at NSLS.

We have made progress in understanding the nature of surface diffuse scattering (i.e., nonspecular reflection) from the surface of polished glass and silicon surfaces. This scattering arises from surface roughness and we believe it can be explained theoretically in terms of a perturbation theory using the exact solution for the reflected wave from an ideal surface and the Fourier transform of the height-height correlation function of the surface. We have developed this theory and are in the process of ana-

lyzing data taken on the RAXS. Further studies of glass and silicon with the surfaces modified to control the surface roughness will be carried out in the next year.

We have investigated the structure of silicon surfaces coated with silanes of varying hydrocarbon length and termination. We have found previously unreported X-ray damage of the monolayers and with XPS analysis the damage has been identified as the presence of oxygen bonded to the carbon atoms. This damage appears to affect the specular reflection at large angles. Studies to quantify and reduce the damage will be carried out in the next months with a preliminary chamber that will allow control of the gross features of the atmosphere surrounding the sample; i.e., O₂ content of the vapor. Further studies may eventually require the design and construction of a chamber allowing more sophisticated control of the atmosphere.

The structure of the silanes have been analyzed by applying newly developed numerical procedures to reflection data taken at Brookhaven National Laboratory. The density of the hydrocarbon layer is about the same as for bulk hydrocarbon liquids. The widths of the interfaces between the vacuum/hydrocarbon and hydrocarbon/silicon oxide layers are both approximately 3 Angstroms. Partially formed silane layers are shorter suggesting tilted molecules. In addition the width of the vacuum/hydrocarbon interface is larger (i.e., 5 Angstroms) than the corresponding interface in the fully coated layer. This indicates that the surface is rougher and we plan to try and measure the diffuse scattering from this roughness.

There is a SiO₂ layer on the surface of the bulk Si that is generally believed to be between 10 Å and 20 Å thick. Model calculations of the effect of such a layer on the X-ray reflectivity indicate that the effect should be measurable. We may have seen such effects in the data taken at BNL last fall, however further experiments are necessary to confirm this interpretation.

We have also investigated the use of X-ray scattering to study chemical changes in the silane monolayers. Preliminary results indicate that this should be a very practical technique once we have learned how to control the degree of X-ray induced damage. This should prove an avenue for future research.

ANNUAL REPORT OF PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

b. Papers Published in Refereed Journals

P. S. Pershan, A. Braslau, A. H. Weiss, and J. Als-Nielsen, "Smectic Layering at the Free Surface of Liquid Crystals in the Nematic Phase: X-Ray Reflectivity," *Phys. Rev. A* **35**, 4800 (1987). (Partial support from NSF Grants DMR-86-14003 and DMR-85-13523.).

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

P. S. Pershan, "Liquid and Liquid Crystal Surfaces," *Proc. National Acad. Sci., USA* **84**, 4692 (1987). (Partial support from NSF Grants DMR-86-14003 and DMR-85-13523.).

B. Ocko, "Layering at Surfaces," Gordon Conference, Liquid Crystals, Brewster Academy, Wolfeboro, New Hampshire (June 22-26, 1987). (Partial support from NSF Grants DMR-86-14003 and DMR-85-13523.).

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

S. Amador, and P. S. Pershan, "Light-scattering Study of the Smectic-C to Smectic-A Transition in Thin, Freely Suspended Liquid Crystal Films," *Bull. Am. Phys. Soc.* **32**, 474 (1987). (Partial support from NSF Grants DMR-86-14003 and DMR-85-13523.).

I. M. Tidswell, S. R. Wasserman, B. M. Ocko, and P. S. Pershan, "X-Ray Grazing Incidence Reflectivity Studies of Silane Coated Polished Silicon," *Bull. Am. Phys. Soc.* **32**, 452 (1987). (Partial support from NSF Grants DMR-86-14003 and DMR-85-13523.).

j. **Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1987.**

Dr. B. Ocko and Mr. I. Tidswell.

I.9 Novel Quantum Effects in Ultra-Small Josephson Junctions. M. Ianisiti, A. T. Johnson, C. J. Lobb, and M. Tinkham, Contracts N00014-83-K-0383, N00014-84-K-0465, and NSF Grant DMR84-04489; Research Unit 4.

During the past year, we have made remarkable progress [1] in exploring new types of quantum effects that occur in ultra-small Josephson junctions at very low temperatures. This research was made possible by our newly developed clean room facility and *e*-beam writing capability for patterning very small thin-film structures, developed with the motivation of studying the properties of low capacitance junctions for detectors and mixers in the submillimeter wave region. It also requires the use of our helium dilution refrigerator (purchased with NSF and Harvard funds) to reach the millidegree temperature range where the quantum effects most clearly dominate over the classical thermally activated processes. Although these experiments are aimed purely at elucidating basic device physics, in some recent experiments a variation of the configuration used for them has shown potential as a prototype 3-terminal device.

The junctions under study are Sn-SnO_x-Sn tunnel junctions, with areas of 0.1 (μm)² or less, so that their intrinsic capacitance is of order 1 femtofarad (fF). With such small capacitances, the charging energy $e^2/2C$ associated with a single electron imbalance between the electrodes is comparable with kT at 1 K, with the energy gap in the Sn banks, and with the Josephson coupling energy $E_J = \hbar I_c/2e$. This is a regime never before explored, especially when the temperature is lowered by a factor of ~ 150 to ~ 20 mK where the thermal processes are almost completely frozen out.

The most striking observation is the temperature dependence of the critical current shown in Figure I.2 (note the logarithmic scale). Focusing first on the small area,

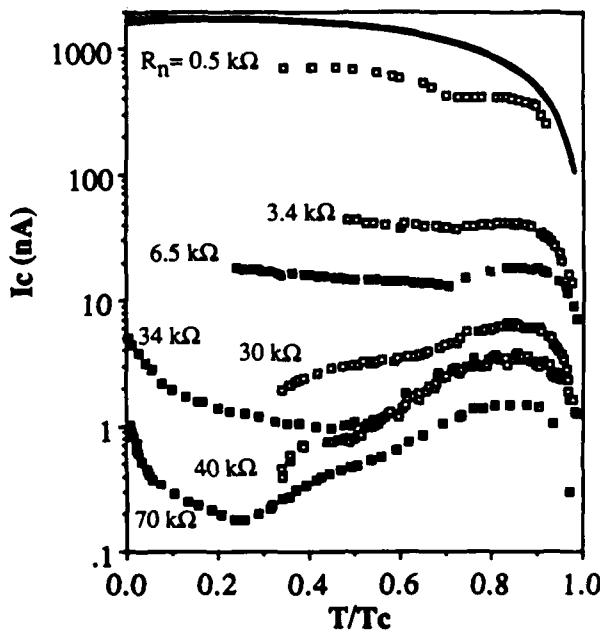


Figure 1.2. I_c vs. T for all samples. Solid line is $I_{co}(T)$ for $R_n = 550 \Omega$.

high resistance junctions in the lower part of the figure, as one cools below the superconducting critical temperature T_c , I_c first rises, then falls by as much as an order of magnitude, and then rises again by a similar amount. The value at $T = 0$ is typically an order of magnitude less than that of a classical junction of the same resistance, as determined by the Ambegaokar-Baratoff relation, which is known to work well for larger junctions with lower resistance. Moreover, for these small high resistance junctions, the measured $I_c(0)$ scales with R_n^{-2} rather than scaling with R_n^{-1} as in the conventional Ambegaokar-Baratoff regime. We can account for both these facts by invoking the capacitive charging energy, which forces a partial delocalization of the phase difference across the junction because of the quantum conjugate relation between the phase and the number of transferred electrons. Qualitatively, the spread-out probability distribution of the phase φ is less strongly bound to the minimum of the Josephson coupling energy $-E_J \cos \varphi$ than a localized semi-classical phase variable would be, so a smaller current (which acts to “tilt” the cosine potential) is sufficient to cause rapid phase evolution (in the “tilt” direction) and a jump to the high-voltage

(gap voltage) state.

Explanation of the entire doubly-reentrant temperature dependence of I_c requires inclusion of thermal activation effects as well as these quantum effects. According to our analysis, the initial rise near T_c and the subsequent fall can be understood as being determined by the "retrapping" critical current, below which the damping is sufficient to cause retrapping in the cosine potential rather than runaway, after an initial activation. Although this reentrance arises from a classical effect, it had never been studied before because it only shows up in very high resistance junctions, where thermal activation over the cosine potential barrier is very easy. As one cools further, the retrapping current I_r continues to approach zero as the quasiparticle damping freezes out. However, the I-V curve becomes hysteretic, with I_c bottoming out and rising again as one approaches the lowest temperatures. This rise occurs at temperatures low enough to finally freeze out the thermal activation over the barrier energy E_J .

Another remarkable observation is that these junctions show a finite resistive voltage *even below* the critical current I_c , indicating a finite rate of phase evolution, again completely contrary to conventional junctions in which there is *no* phase slip until the jump to the gap voltage at I_c . Our interpretation of this voltage is that it arises from MQT (Macroscopic Quantum Tunneling) of the phase from minimum to minimum which is prevented from running away because of damping effects. Of course, as T increases, thermally-activated phase motion also plays a role. We can give at least a qualitative description of the temperature dependence of this initial resistance in this way.

All these phenomena: the severe reduction of $I_c(0)$, the remarkable temperature dependence of $I_c(T)$, and the temperature-dependent resistance $R_0(T)$ below I_c , are to the best of our knowledge new observations, and our interpretations involve new theoretical considerations. This work is continuing, as we explore the effects of

applied magnetic fields strong enough to reduce I_c to zero, and even strong enough to destroy the superconductivity in the banks. In the latter regime, we are observing single particle tunneling, in which the charging energy shows up as an "offset" of the I-V curve by a voltage $e/2C$ on either side of zero. This has been explained by Averin and Likharev [2] in terms of a "Coulomb blockade", and it provides an independent measure of the appropriate value of C to be taken. This is an important consideration, because with C in the femtofarad range, stray capacitance effects could be very severe. In fact, it appears that the simple geometric capacitance of these tiny junctions is essentially correct for the phenomena under study. The reason for this surprising result is still not clear, but it presumably will provide new insights into the detailed physics of the tunneling process when it is discovered.

Reference:

1. M. Iansiti, A. T. Johnson, W. F. Smith, H. Rogalla, C. J. Lobb, and M. Tinkham, *Phys. Rev. Lett.* **59**, 489 (1987).
2. D. V. Averin and K. K. Likharev, *J. Low Temp. Phys.* **62**, 345 (1986).

I.10 High T_c Superconductors. G. Spalding, L. Ji, C. J. Lobb, and M. Tinkham, NSF Grant DMR 86-14003 and N00014-84-K-0465; Research Unit 4.

With the discovery of the family of oxide superconductors, with presently known materials having T_c as high as 95 K, new vistas have been opened for the application of superconducting devices in applications which were not practical with superconductors requiring refrigeration to liquid helium temperatures. Of course, if we can find materials which show reproducible and useful superconductivity at room temperature, the potential applications are truly revolutionary. Among the applications that might be made with the existing new materials, electronic applications such as SQUID sensors operating at LN_2 temperatures appear closer to realization than large magnet coils, for example. Accordingly, we have begun an active program of research with

these materials, with the potential for electronics applications in mind.

Although electronics applications will require thin film material, our first step was to develop the capability of making pellets of bulk material, with emphasis on the "123 material" $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$. Using furnaces in the Materials Science area here in the Gordon McKay laboratory, we have made pellets of material with X-ray diffraction patterns in excellent agreement with published ones for high-quality samples. These materials also show good resistive transitions. With this starting material as a target, we have made thin films by ion-beam sputtering. Although we had expected that this process would maintain stoichiometry better than other sputtering techniques, it still took a bit of cut and try to obtain films with reasonably good transitions after annealing in oxygen. As an alternative, which was pioneered at Bellcore, we have also experimented with the use of a pulsed excimer laser (also from the Materials Science Group) to ablate material from pellet to substrate. Preliminary results have been encouraging with this technique as well.

Both of these techniques were chosen because we do not have a 3-source sputtering or evaporation system, needed in order to produce the superconducting film directly from the separate elements. Although these methods starting from pellet material have this advantage, the multiple source direct process has more flexibility, especially in searching for new and as yet undiscovered compounds that might have superior properties, particularly higher T_c values. Accordingly, we are trying to obtain funding for such a more versatile deposition system. However, our preliminary work suggests that we can make useful exploratory experiments with our less elaborate system, perhaps by collaborating with other laboratories (such as Bellcore) in the preparation of samples.

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

b. Papers Published in Refereed Journals

Q. Hu, C. J. Lobb, and M. Tinkham, "Response of Josephson Junctions to Far-Infrared Radiation Near Their Plasma Resonance Frequencies," *Phys. Rev. B* 35 1687-1691 (1987). (Partial support from ONR N00014-83-K-0383).

M. Iansiti, A. T. Johnson, W. F. Smith, H. Rogalla, C. J. Lobb, and M. Tinkham, "Charging Energy and Phase Delocalization in Single Very Small Josephson Tunnel Junctions," *Phys. Rev. Lett.* 59, 489-492 (1987). (Partial support from NSF DMR-84-04489 and ONR N00014-83-K-0383).

M. Iansiti, A. T. Johnson, W. F. Smith, C. J. Lobb, and M. Tinkham, "Possible Observation of Charging Energy Effects in Single Ultra-Small Josephson Tunnel Junctions," *Proc. 18th Int. Conf. on Low Temperature Physics*, Kyoto, 1987, *Japanese Journal of Applied Physics* 36, 1557-1558 (1987). (Partial support from NSF DMR-84-04489 and ONR N00014-83-K-0383).

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

Q. Hu, C. J. Lobb, and M. Tinkham, "Response of Josephson Junctions to Far-Infrared Radiation Near Their Plasma Resonance Frequencies," March Meeting of American Physical Society, New York, NY, 1987.

A. T. Johnson, Q. Hu, M. Tinkham, C. S. L. Chun, and M. Bhushan, "High Frequency Measurements of Josephson Junction Arrays," March Meeting of American Physical Society, New York, NY, 1987.

M. Iansiti, A. T. Johnson, W. F. Smith, C. J. Lobb, and M. Tinkham, "Possible Observation of Charging Energy Effects in Single Ultra-Small Josephson Tunnel Junctions," 18th International Conference on Low Temperature Physics, Kyoto, Japan, 1987.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1987

Dr. H. Rogalla, Mr. Q. Hu, and Mr. S. P. Benz.

I.11 Nonlinear Dynamics of Electronic Neural Networks. K. L. Babcock, C. Marcus, and R. M. Westervelt, Contract N00014-84-K-0465; Research Unit 5.

Electronic neural networks composed of nonlinear threshold switching elements hold considerable promise for the solution of problems in pattern recognition and for the simulation of certain complex physical processes. As hardware implementations progress, questions of stability in real networks with finite delays become important. A related problem is the measurement and manipulation of the set of initial patterns, called the basin of attraction, which converge onto the stored pattern or "memory". We are studying these problems from the point of view of nonlinear dynamics, using our experience in this field on problems in semiconductor transport and on the structure of basins of attraction in driven oscillators. Other workers at Harvard in this field are Prof. John Daugmann, who has studied problems in visual pattern recognition, and Prof. Arthur Jaffe, who is an expert in mathematical physics, and spin glass theory in particular. In addition, a group of faculty in computer science and mathematics works on natural information processing in relation to visual images.

In the past year a new student, Charles Marcus, has joined the research program and has begun to study the problems of the shapes of basins of attraction and the stability of electronic neural networks as described below. Our work has resulted in three publications, an invited presentation at the Snowbird Conference on "Neural Networks for Computing" last April, and an oral presentation at the upcoming conference on neural networks in Boulder, Colorado in November, 1987.

Linear Stability Analysis of Small Neural Networks — We have finished our initial analysis of the stability and structure of the basins of attraction of small electronic neural networks composed of two and three threshold-switching devices. This work was based primarily on a linear stability analysis of the circuit along with digital simulations of the nonlinear equations. Our results show that finite response time of neurons introduces both damped and active oscillatory modes which influence the

shapes of the basins of attraction.

Electronic Neural Network with Delay — We have constructed and tested an electronic neural network composed of eight neurons, which was designed to measure the shapes of basins of attraction and to test the stability of different configurations. Special features of this network are a controllable analog delay for each neuron, and an interfaced graphics display to measure the shape and topology of basins of attraction. Because basins of attraction are determined by direct search of the space of initial conditions, their measurement is very slow on even the fastest digital computers, and the measurement of actual networks is necessary. Digital simulations are used primarily to check the results.

Basins of Attraction — Using our analog network we have measured the basins of attraction for neural networks of different configurations under different circumstances. This is done by repetitively loading initial conditions from a two-dimensional plane of initial conditions, which are the raster scanned across a display. The final state which corresponds to each initial condition is indicated on the display. By moving this plane through the higher dimensional space of all initial conditions (n -dimensional for an n -neuron network) we obtain information about the shape and topology of the basins of attraction. For an ideal network with fast neuron time response and few stored memories, we measure smooth basins of attraction of comparable size, as found previously. The same apparatus is used to study memory overloading with fast neurons. When the number of stored memories is too large, the basins of attraction deform, and their relative sizes and locations can vary greatly. For added time delays at each neuron, the network can develop active oscillatory modes for certain initial conditions. The basins of attraction for these oscillatory modes are typically twisted, and they complicate the shapes of neighboring stable memories.

Oscillatory Modes — When the neuron time-delay becomes comparable to the input RC time, the network typically develops oscillatory modes, with corresponding

basins of attraction. Using our electronic neural network, mathematical analysis, and digital simulations, we have studied the relative stability of different configurations of neurons. We find that large loops are relatively stable due to saturation of the input-output characteristics. However, configurations of an odd number of neurons each symmetrically interconnected to one another by negative couplings are relatively unstable. These "frustrated" patterns of neurons occur quite often in some proposed schemes for neural networks and our results suggest they should be avoided.

Relation to Larger Networks — In order to relate results from our small 8-neuron network to larger more realistic networks, we have studied the decomposition of different models for larger networks into smaller geometrical structures, using results from graph theory. We find that partially interconnected networks typically contain many smaller structures of the form we study using the electronic network with delays. We hope to use this analysis to help develop "defect" models for the stability of larger networks.

ANNUAL REPORT OF PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

K. L. Babcock and R. M. Westervelt, "Dynamics of Simple Electronic Neural Networks," *Physica D*, in press. (Partial support from ONR N00014-84-K-0329).

b. Papers Published in Refereed Journals

K. L. Babcock and R. M. Westervelt, "Stability and Dynamics of Simple Electronic Neural Networks with Added Inertia," *Physica 23D*, 464-469 (1986).

K. L. Babcock and R. M. Westervelt, "Complex Dynamics in Simple Neural Circuits," Proc. Conf. Neural Networks for Computing, 151, Snowbird, UT, 1986 (J. S. Denker, Ed.), American Institute of Physics, New York, (1986).

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

R. M. Westervelt and C. Marcus, "Nonlinear Dynamics of Electronic Neural Networks," Conference on Neural Networks for Computing, Snowbird, UT, April 1987.

i. Honors/Awards/Prizes

Named to Board of Editors, *Physica D*, "Nonlinear Phenomena."

Elected Co-chairman 1988 Gordon Conference on Condensed Matter Physics, "Nonequilibrium Phenomena."

j. Graduate Students and Postdoctorals Supported by JSEP for the Year Ending 1 October 1987

Mr. Kenneth L. Babcock and Mr. Charles Marcus.

II. QUANTUM ELECTRONICS

Personnel

Prof. N. Bloembergen
Prof. C. Cordero (Summer)
Asst. Prof. E. Mazur
Assoc. Prof. T. W. Mossberg
Dr. Y. S. Bai
Dr. Arturo Lezama
Dr. L. A. Lompré (Summer)

Dr. A. M. Malvezzi
Mr. W. R. Babbitt
Mr. K. H. Chen
Mr. J. E. Golub
Ms. E. Rosenberg
Mr. J. Wang

II.1 Time-Domain Frequency-Selective Optical Data Storage. J. E. Golub and T. W. Mossberg, Contracts N00014-84-K-0465 and ARO DAAG 29-83-K-0040; Research Unit 6.

We have continued our study of the storage of optical waveforms in inhomogeneously broadened absorbers. Over the last few years, we have concentrated on the studies of the basic mechanisms involved in the storage of optical pulse shapes. In this first stage of our work, we utilized gas-phase optical absorbers. Such samples are simple and well understood. We could, therefore, concentrate on the nonlinear optical aspects of the program and avoid complications associated with unknown material properties. Work in gas-phase absorbers has allowed us to gain a relatively complete understanding of the physics of time-domain frequency-selective optical data storage [1]. This work has been described in previous annual reports.

In the last interval, our attention shifted to materials problems related to time-domain memory systems. In particular, we have studied the optical properties of the crystal $\text{Eu}^{3+}:\text{Y}_2\text{O}_3$. We have measured optical dephasing times and their temperature dependence, we have measured the decay times of population imbalances created in ground-electronic-state nuclear quadrupole levels, and we have actually

demonstrated the storage and recall of temporally complex optical pulses from the crystal. Storage times of minutes limited only by laser frequency instability have been realized. We find that quadrupole-level thermalization times, which set the limit on how long one can store an optical waveform, exceed 60 hours at 4.5 Kelvin. We have also performed a complete analysis of the hyperfine splittings of the Eu^{3+} levels in this crystal.

Our preliminary solid-state work seems to indicate that cryogenic materials do, in fact, possess qualities that will ultimately make ultra-high speed, high-density optical memories possible.

Reference:

1. T. W. Mossberg, *Opt. Lett.* **7**, 77 (1982).

II.2 Termination of Research Unit. T. W. Mossberg, Contract N00014-84-K-0465; Research Unit 6.

As indicated in the last proposal, a major objective of this unit during the current reporting interval has been to carry out an orderly completion of its operations. This has been accomplished. In the process, three students supported through the JSEP program received their Ph.D. degrees.

JSEP support of this unit over the years has resulted in 25 journal publications, four Ph.D. dissertations, and one patent.

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

W. R. Babbitt and T. W. Mossberg, "Time-Domain Frequency-Selective Optical Data Storage in a Solid-State Material," *Opt. Commun.*

f. Patents Granted

U.S. Patent 4,670,854. *Optical Cross-Correlation and Convolution Apparatus.* Filed September 30, 1985 — Issued June 2, 1987. T. W. Mossberg, Y. S. Bai, W. R. Babbitt, and N. W. Carlson. Assigned to President and Fellows of Harvard College.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

J. E. Golub, Y. S. Bai, and T. W. Mossberg, "Fundamental Spectroscopy of Dressed-State Polarized Atomic Samples," International Quantum Electronics Conference, Baltimore, MD, 1987.

j. Graduate Students and Post-Doctorals Supported Under JSEP for the Year Ending 1 October 1987

Dr. Arturo Lezama, Dr. Y. S. Bai, Mr. W. R. Babbitt, Mr. J. E. Golub, and Ms. E. Rosenberg.

II.3 Nonlinear Four-Wave Mixing in Vapors. N. Bloembergen, Contract N00014-84-K-0465; Research Unit 7.

The experimental research project on collision-induced coherence has been terminated. Professor Bloembergen has given numerous review lectures on this

comprehensive topic of continuing current interest during his sabbatical travels in 1987. These invited lectures were presented at institutes in Munich, Giessen, Hanover, Zürich, Leiden, Helsinki, Shanghai, Beijing and Guangzhou.

II.4 Picosecond Laser Interactions with Semiconductors. A. M. Malvezzi, and N. Bloembergen, Contract N00014-84-K-0465; Research Unit 7.

During 1987 the reflectivity of the high temperature phase of carbon, created by a picosecond pump pulse, has been measured by a picosecond probe pulse for different angles of incidence, for both *s*- and *p*-polarization, at wavelengths of 1.06 μm and 0.53 μm . In particular, a shift in the minimum of the reflectivity for polarization in the plane of incidence near the Brewster angle has been observed. From these data both the real and imaginary part of the index of refraction of the high temperature phase of carbon can be determined. They are both smaller than in the low temperature graphite phase. These experiments with near-grazing angles of incidence up to 80°C unambiguously eliminate the possibility of distortion of the data by effects of vaporized carbon.

A new experimental arrangement is planned in which the reflectivity of the high temperature phase will be measured with a white light pulse. Simultaneous spectral and temporal resolution will be obtained by means of a Hamamatsu scanning oscilloscope and a multichannel analyzer. Such data will permit plotting of the dielectric function over a frequency interval from the near infrared to the near ultraviolet, from which more detailed information about the electronic structure of the high temperature phase of carbon may be obtained.

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

b. Papers Published in Refereed Journals

N. Bloembergen, "A Quarter Century of Stimulated Raman Scattering," *International Journal of Modern Physics B*, 1-8 (1987). This same paper will also be published in the October 1987 issue of *Pure and Applied Chemistry*.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

A. M. Malvezzi, "Interaction of Picosecond Laser Pulses with Solid Surfaces," *SPIE Advances in Semiconductors and Semiconductor Structures*, Bay Point, Florida, March 22-27, 1987.

A. M. Malvezzi, "Interaction of Picosecond Laser Pulses with Graphite," *SPIE International Symposium on Optical and Optoelectronic Applied Science*, the Hague, Netherlands, March 30-April 3, 1987.

N. Bloembergen, "Laser Applications in Science and Technology," Walter Schottky Lecture, Aachen, FRG, April 9, 1987.

N. Bloembergen, "Collision-Induced Coherence," Conference on Laser Induced Processes in Matter, Quantum Electronics Division of the European Physical Society, Helsinki, Finland, August 15-17, 1987.

h. Honors/Awards/Prizes

N. Bloembergen, Honorary Professorship, Fudan University, Shanghai, PRC, May 13, 1987.

N. Bloembergen, Hon. Docteur-es-Sciences, Laval University, Quebec, Canada, November 7, 1987.

II.5 Multiphoton Vibrational Excitation of Molecules. E. Mazur, J. Wang, and K. H. Chen, Contracts N00014-84-K-0465 and ARO DAAG29-85-K-0060; Research Unit 8.

Infrared multiphoton excitation and dissociation of polyatomic molecules by infrared laser radiation, and the isotope selectivity of this process have received considerable interest in the past years. In this research unit the dynamics of infrared multiphoton excited polyatomic molecules is studied by time-resolved spontaneous and coherent Raman scattering. The Raman spectrum reflects the intramolecular energy distribution of the probed molecules. A large number of data on infrared multiphoton excited molecules ranging in size from 5 to 8 atoms were obtained in the work funded under the above contract [1]-[3]. Most of the molecules studied have more than one Raman active mode and thus allow direct observation of the intramolecular distribution of vibrational energy among the modes after the infrared multiphoton excitation. During the past reporting period work was done on two aspects: (1) the "localization" of energy in CF_2Cl_2 reported in the previous reporting period was further investigated, and (2) a new setup to obtain more detailed information on the dynamics on infrared multiphoton excited molecules was built and its performance tested.

Measurements on the ν_8 pump mode of CF_2Cl_2 were completed. This molecule has four Raman active modes of which we studied three after infrared multiphoton excitation. The results show a *distinct nonequilibrium distribution* [3]-[4]. Apparently the energy remains *partly localized* in the pump mode up to a total internal energy of about $10,000 \text{ cm}^{-1}$. If part of the energy remains localized in a small set of modes it may be possible to induce reactions that are not thermodynamically favored. If N_2 buffer gas is added, collisional relaxation of energy takes place, and a clear trend toward equilibrium is observed. The behavior of the Raman

signal intensities with increasing laser fluence shows that complete randomization of vibrational energy does not occur even at the highest fluence at which Raman signals were measured.

At very high fluence the molecules dissociate and the Raman probe laser induces a broadband fluorescence from the dissociation fragments. We studied this fluorescence in detail and found that (a) the dissociation fragments carry a considerable amount of energy (up to 5000 cm^{-1}), and (b) the unimolecular dissociation rate of infrared multiphoton excited CF_2Cl_2 must be much smaller than the excitation rate [3].

We have prepared four papers on the spontaneous Raman spectroscopy measurements of the infrared multiphoton excited molecules. One of them, a review paper of the work funded under this contract, is an invited contribution to a special issue of *Laser Chemistry* on multiphoton excitation. The above-mentioned work was also presented at a number of international conferences.

In addition to the ongoing experiments, equipment purchased with funding obtained through the DoD University Research Instrumentation Program for a coherent anti-Stokes Raman spectrometer (CARS) has been made operational. The system consists of two Nd:YAG laser-pumped dye lasers: one narrowband (0.01 cm^{-1}) and one broadband (200 cm^{-1}). Both lasers have been successfully amplified in two stages, yielding energies of 10 and 20 mJ, respectively. The apparatus was tested with liquid and gaseous samples, and CARS signals were obtained for both samples. With these two lasers we will study the *multiplex* CARS signals from infrared multiphoton excited molecules. The multiplex probing scheme allows signals from the various vibrational levels to be measured simultaneously. During the next reporting period we will synchronize the CARS lasers with the CO_2 -laser and study the CARS signals from molecules pumped by the CO_2 -laser.

The CO₂-laser amplifier, which is about eight years old now and is a workhorse for the present type of measurements, still is a point of major concern. It has exceeded its operational lifetime many times, and unfortunately requires constant servicing. This has increased operating costs and interferes with the research. Measurements are presently carried out mainly with longer (10 ns) pulses that do not require broadband amplification. A complete factory overhaul and retrofit of the high-pressure amplifier (the current unit is one of the first ever manufactured) may not be cost-effective. We are therefore also studying different replacement options for the next contract period. A possibility would be to rebuild a simpler, more effective laser system for generating 100 mJ picosecond infrared laser pulses without amplification, for instance by mode-locking a standard CO₂-laser. We are also investigating the possibility of optically pumping CO₂-lasers. For this purpose we have established contacts with Dr. Gunnar Wang from the Norwegian Defense Research Establishment, who has experience in this field.

We plan to continue our work on both fronts: First, we will complete our work on the time-resolved *spontaneous* Raman spectroscopy of infrared multiphoton excited molecules. Second, we will gradually replace the spontaneous Raman technique by *coherent* anti-Stokes Raman spectroscopy, which is more sensitive and which has a higher resolution. The spontaneous Raman work will be extended by studying CF₂Cl₂ pumped on a *different* infrared active mode (ν_1), to see if one can also localize energy in that mode. At the same time the CARS spectrometer will be further tested and synchronized with the CO₂-lasers.

References:

1. Jyhpyng Wang, Kuei-Hsien Chen, and Eric Mazur, "Time-resolved Spontaneous Raman Spectroscopy of Infrared Multiphoton Excited SF₆," *Phys. Rev. A* **34**, 5 (1986) 3892.

2. Eric Mazur, Kuei-Hsien Chen, and Jyhpyng Wang, "The Interaction of Infrared Radiation with Isolated Molecules: Intramolecular Nonequilibrium," *Lasers 1986 Proceedings (SOQUE 1987)*.
3. Jyhpyng Wang, Kuei-Hsien Chen, and Eric Mazur, "Raman Spectroscopy of Infrared Multiphoton Excited Molecules," *Laser Chemistry*, January 1988.
4. Kuei-Hsien Chen, Jyhpyng Wang, and Eric Mazur, "Nonthermal Intramolecular Energy Distribution in Isolated Infrared Multiphoton Excited Molecules," *Phys. Rev. Lett.*

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

Kuei-Hsien Chen, Jyhpyng Wang, and Eric Mazur, "Nonthermal Intramolecular Vibrational Energy Distribution in Infrared Multiphoton Excited CF_2Cl_2 ," *Phys. Rev. Lett.* (Partial support from ARO DAAG 29-85-K-0060)

Jyhpyng Wang, Kuei-Hsien Chen, and Eric Mazur, "Raman Spectroscopy of Infrared Multiphoton Excited Molecules," *Laser Chemistry*, January 1988. (Partial support from ARO DAAG 29-85-K-0060)

b. Papers Published in Refereed Journals

Jyhpyng Wang, Kuei-Hsien Chen, and Eric Mazur, "Time-resolved Spontaneous Raman Spectroscopy of Infrared Multiphoton Excited SF_6 ," *Phys. Rev. A34*, 5 (1986) 3892. (Partial support from ARO DAAG 29-85-K-0060)

c. Books (and sections thereof) Submitted for Publication

Eric Mazur, Kuei-Hsien Chen, and Jyhpyng Wang, "Highly Nonthermal Intramolecular Energy Distribution in Isolated Infrared Multiphoton Excited CF_2Cl_2 ," in *Laser Spectroscopy VIII*, ed. S. Svanberg (Springer Verlag). (Partial support from ARO DAAG 29-85-K-0060)

Eric Mazur, "The Interaction of Intense Picosecond Infrared Pulses with Isolated Molecules," in *Atomic and Molecular Processes with Short Intense Laser Pulses*, ed. A. Bandrauk (Plenum). (Partial support from ARO DAAG 29-85-K-0060)

d. Books (and sections thereof) Published

Eric Mazur, Kuei-Hsien Chen, and Jyhpyng Wang, "The Interaction of Infrared Radiation with Isolated Molecules: Intramolecular Nonequilibrium," *Lasers 1986 Proceedings (SOQUE 1987)*. (Partial support from ARO DAAG 29-85-K-0060)

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

Eric Mazur, Kuei Hsien Chen, and Jyhpyng Wang, "Highly Nonthermal Intramolecular Energy Distribution in Isolated Infrared Multiphoton Excited CF_2Cl_2 Molecules," *EICOLS 1987 Conference*, Åre, Sweden, June 1987. (Partial support from ARO DAAG 29-85-K-0060)

Eric Mazur, "The Interaction of Intense Picosecond Infrared Laser Pulses with Isolated Molecules," *NATO Advanced Research Workshop*, Lennoxville, Canada, July 1987. (Partial support from ARO DAAG 29-85-K-0060)

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

Kuei-Hsien Chen, Jyhpyng Wang, and Eric Mazur, "Thermal and Nonthermal Intramolecular Energy Distributions in Isolated Infrared Multiphoton Excited Molecules," *March APS Meeting*, New York, 1987. (Partial support from ARO DAAG 29-85-K-0060)

Eric Mazur, "Nonthermal Intramolecular Vibrational Energy Distribution in Isolated Infrared Multiphoton Excited CF_2Cl_2 Molecules," *ICOMP IV Conference*, Boulder, July 1987.

j. Graduate Students and Postdoctorals Supported Under JSEP for the Year Ending 1 October 1987

Prof. C. Cordero (Summer), Dr. L. A. Lompré (Summer), Mr. Kuei-Hsien Chen, and Mr. Jyhpyng Wang.

III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

Personnel

Prof. R. W. Brockett	Mr. G. Feigen
Asst. Prof. J. J. Clark	Mr. D. Friedman
Prof. Y. C. Ho	Mr. M. Fu
Assoc. Prof. D. D. Yao	Mr. P. Glasserman
Dr. X. Cao	Mr. W. Gong
Dr. R. Conterno	Mr. J. J. Hu
Dr. A. Yuille	Mr. M. Lee
Mr. A. Bangs	Mr. S. Li
Mr. D. Cochran	Mr. P. Vaikili
Mr. J. Dille	Mr. M. Zananis

III.1 Development of a High Resolution Magnetic Sensor Array. J. J. Clark, R. W. Brockett, and D. Friedman, Contracts N00014-84-K-0465 and N00014-84-K-0504; Research Unit 9.

In the preceding year we have begun a program concerned with the design and development of integrated sensor arrays for use in robotics applications. A 64 by 64 element array has been designed and fabricated in a 3 micron CMOS process. The magnetic sensing elements are split-drain mosfet devices [1], and measure 96 microns square. The outputs of these split drain magfets are amplified and converted to a voltage by current mirrors, followed by a buffer amplifier. The array is scanned in a raster scan fashion with on-chip scan circuitry. Measurements have been made on the fabricated array which show that the sensing element/current mirror/amplifier combination has a sensitivity of about 6 volts/Tesla (or 0.6 mV/Gauss). The sensors are quite linear over the range of 0 to 10 K Gauss. Experiments with a rare earth magnet whose surface field is about 2.5 K Gauss, have shown that, at a distance of

0.5 cm from the sensor plane, the sensitivity of a sensing element to lateral displacement of the magnet (whose N-S axis is parallel to the sensor plane) is 25 mV/mm, when the magnet is directly over the sensing element. This corresponds to a 2.5 mV difference in the output between adjacent sensing elements. The maximum useful clock rate of the prototype array was seen to be around 200 Khz, which at 4096 sensing elements/frame and one clock cycle per sensing element works out to a frame rate of about 50 frames per second. This number is adequate for the tactile sensing application we are considering, but can certainly be improved upon. One problem that appeared in the array manifested in a nonuniformity of sensor response between columns of the array. This nonuniformity was due to slight, process-induced, variations of the width of the current mirror transistors (each column shared a current mirror). This caused a variation in the offset and gain of the sensing element. We are presently designing a new prototype which shares a single current mirror between columns and thereby eliminates this uniformity problem.

We have simulated a version of the magnetic sensor array which performs spatial filtering of the magnetic field pattern on-chip. This is done by summing the output of a number of the split-drain devices before feeding the currents into the current mirror. By adjusting the gate potentials on the split drain fets one can obtain weightings of the elements in the spatial summation and hence perform an arbitrary spatial convolution. Negative weights are obtained by electronically swapping the outputs of the two drains of the split-drain device. We plan, in the coming year, to fabricate a prototype of any array that computes the Laplacian of the magnetic field.

References:

1. P. W. Fry and S. J. Hoey, "A Silicon Magnetic Field Transducer of High Sensitivity," *IEEE Transactions on Electron Devices* **16**, 35-39 (1969).

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

b. Papers Published in Refereed Journals

J. J. Clark, "Singularities of Contrast Functions in Scale Space," First IEEE Int. Conf. on Computer Vision, London, England, pp. 491-496, 1987.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

J. J. Clark, "Singularities of Contrast Functions in Scale Space," First IEEE Int. Conf. on Computer Vision, London, England, pp. 491-496, 1987.

III.2 Decision and Control — Discrete Event Dynamic Systems Study. Y. C. Ho, D. Yao, and R. Conterno, Contracts N00014-84-K-0465, ONR-N00014-86-K-0075, NSF-ESC-85-15449, and NSF-CDR-85-001-08; Research Unit 10.

Nineteen hundred and eighty-seven can be said to mark the year in which the subject of Perturbation Analysis (PA) of Discrete Event Dynamic Systems (DEDS) finally came into its own both in terms of theoretical foundation and general acceptance.

PA was more or less accidentally discovered as a trick to solve a particular problem in 1978. During the sabbatical of Professor Y. C. Ho in 1981, he first recognized the generalizing possibility of PA and obtained the first experimental evidence of its power to predict gradient of performance measure of general DEDS. Subsequent research on PA extended its range along both theoretical and application fronts. In 1984, it was recognized that the principal theoretical question of PA

has to do with the mathematical question of

$$\frac{d}{d\theta} E[PM(\theta, w)] = ? = E \left[\frac{d}{d\theta} (PM(\theta, w)) \right] \quad (1)$$

where θ = system design parameter(s), PM = Performance Measure of the system, w = samples of all the random variables in the system. The interchangeability of expectation and derivative in equation (1) can be understood intuitively as follows: Is it possible to infer the average behavior of a system under $\theta + d\theta$ by observing its sample behavior under θ alone? That this is not a trivial question can be gleamed from the following simple example. Suppose one changes the routing probability of a part in a complex manufacturing system ever so slightly. Intuitively, this change will cause some slight change in performance such as the average inventory at a particular machine. However, on a sample path basis, an infinitesimal change in routing probability will never cause any change in routing of parts in any finite time interval. Consequently, looking at sample path behavior under θ will not yield knowledge about the same under $\theta + d\theta$, or we cannot use the right side of (1) to estimate its left side. For several years, there has been controversies as to the conditions under which (1) is true and the domain of applicability of PA. On the one hand, we had considerable experimental and insightful evidence that PA is a very general approach. On the other hand, rigorous proof of (1) existed only for a small class of queueing networks. This is finally resolved in PA's favor in 1986-1987 because of a number of significant theoretical developments partially reported last year and now accepted by the scientific community at large. In particular, the smoothed PA and the extended PA techniques [1],[2] demonstrated the generality of the sample path approach.

At the same time, there is now general recognition in both the system theory and operation research field that DEDS is an important research subject for the future. This is so not only because of two white papers issued by the respective societies [3],[4] but a plethora of conferences, workshops, and special issues devoted

to the subject. We feel that in retrospect, 1987 will be remembered as the watershed year in discrete event system theory.

During the past year David Yao has continued his work on the monotonicity and convexity properties of various stochastic processes in discrete event systems, focusing on queueing networks. These are monotonicity and convexity properties with respect to time, initial states as well as other system parameters. These properties characterize *qualitatively* the dynamic behavior of the sample paths of such processes under temporal, spatial and other parametric changes. His work complements perturbation analysis, which *quantitatively* generates the rate of changes under parameter perturbation. He has basically completed the investigation in Markovian networks, having established many results, and is recently extending these results to more general queueing networks driven by point processes. Applying these results, he has solved a variety of resource allocation, optimization and control problems in manufacturing systems and communication networks. Not surprisingly, many parameters in discrete event systems are discrete by nature. To optimize such discrete parameters, the most important algorithm is the so-called "greedy algorithm," which is the equivalent to the steepest descent/ascent algorithm in continuous optimization. Despite its remarkable efficiency, the greedy algorithm does not in general lead to optimality. In fact this optimality issue is closely related to submodular functions and discrete mathematical structures such as matroid and polymatroid. Motivated by a dynamic scheduling problem in multi-media communication networks, Yao has developed efficient algorithms for solving a class of optimization problems over a polymatroid feasible region. He has also been investigating the optimality of greedy algorithms in other control and optimization problems.

References:

1. Y. C. Ho and Shu Li, "Extension of Infinitesimal Perturbation Analysis," *IEEE Transactions on Automatic Control*, 1987.
2. Weibo Gong and Y. C. Ho, "Smoothed Perturbation Analysis of Discrete Event Dynamic Systems," *IEEE Transactions on Automatic Control*, 1987.
3. "A Challenge to Control," Report of a NSF-sponsored conference organized by the IEEE Control System Society, *IEEE Transactions on Automatic Control*, AC-32 (4) 275-285 (1987).
4. "Future Direction of Operation Research," Report of a NSF-sponsored conference organized by ORSA/TIMS May 1987 (to appear).

**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

X. Cao, "Realization Probability in Closed Jackson Queueing Networks and Its Application," *Advances in Applied Probability*, 1987.

X. Cao and Y. C. Ho, "Estimating Sojourn Time Sensitivity in Queueing Networks Using Perturbation Analysis," *Journal of Optimization Theory and Applications*, 1987.

X. Cao and Y. C. Ho, "Perturbation Analysis of Sojourn Times in Closed Jackson Queueing Networks," *Operations Research*.

X. Cao and Y. C. Ho, "Sensitivity Estimate and Optimization of Throughput in a Production Line with Blocking," *IEEE Transactions of Automatic Control*.

Y. C. Ho, "PA Explained," *IEEE Transactions on Automatic Control*, 1987.

Y. C. Ho and Shu Li, "Extension of Infinitesimal Perturbation Analysis," *IEEE Transactions on Automatic Control*, 1987.

P. Glasserman, "Infinitesimal Perturbation Analysis of a Birth and Death Process," *Operation Research Letters*.

Weibo Gong and Y. C. Ho, "Smoothed Perturbation Analysis of Discrete Event Dynamic Systems," *IEEE Transactions on Automatic Control*, 1987.

D. D. Yao, "Optimizing a Majorization Order over a Polymatroid," *Operations Research*.

D. D. Yao and Z. Schechner, "Decentralized Control of Service Rates in a Closed Jackson Network," *IEEE Transactions on Automatic Control*.

J. G. Shanthikumar and D. D. Yao, "Second-Order Properties of the Throughput in a Closed Queueing Network," *Mathematics of Operations Research*.

J. G. Shanthikumar and D. D. Yao, "Optimal Allocation of Buffers in a System of Manufacturing Cells," *Annals of Operations Research*.

J. G. Shanthikumar and D. D. Yao, "Comparing Ordered-Entry Queues with Heterogeneous Servers," *Queueing Systems, Theory and Applications*.

J. G. Shanthikumar and D. D. Yao, "Optimal Server Allocation in a System of Multi-Server Stations," *Management Science* 34 (1987).

J. G. Shanthikumar and D. D. Yao, "Stochastic Monotonicity of the Queue Length in Closed Queueing Networks," *Operations Research* 35 (1987).

J. G. Shanthikumar and D. D. Yao, "Throughput Bounds for Closed Queueing Networks with Queueing-Dependent Service Rates," *Performance Evaluation*.

D. D. Yao "Optimal Run Quantities for an Assembly System with Random Yields," *IIE Transactions*.

D. D. Yao, "The Arrangement of Servers in an Order Entry System," *Operations Research* 35 (1987).

D. D. Yao and J. G. Shanthikumar "Allocating a Joint Setup in a Multi-call System," *Annals of Operation Research*.

b. **Papers Published in Refereed Journals**

D. D. Yao and J. G. Shanthikumar, "The Optimal Input Rates to a System of Manufacturing Cells," *Information Systems and Operational Research* 25, 57-65 (1987).

Y. C. Ho, "Performance Evaluation and Perturbation analysis of Discrete Event Dynamic Systems," *IEEE Transactions on Automatic Control* AC-32, (1987).

P. Glasserman, "Sensitivity of Sample Values not Generated by Inversion," *J. of Opt. Th. and Appl.* 52, 487-493 (1987).

D. Teneketzis and Y. C. Ho, "The Decentralized Wald Problem," *Information*

and Computation 73, 23-44 (1987).

Note: David Yao has six other publications during the past year that are based on work done at Columbia University before he joined the Harvard faculty.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

Y. C. Ho, SIAM Applied Probability Conference, New Brunswick, NJ, January 9, 1987.

Y. C. Ho, Conference on Intelligent Control, January 19, 1987.

Y. C. Ho, Boston University Conference on Manufacturing Automation, January 30, 1987.

Y. C. Ho, R and A Conference, April 1, 1987.

Y. C. Ho, Boston University, April 10, 1987.

Y. C. Ho, TIMS/ORSA National Meeting, May 5, 1987.

Y. C. Ho, Ninth Symposium on Sensitivity in Mathematical Programming, May 20, 1987.

Y. C. Ho, MIT Manufacturing Conference, June 6, 1987.

Y. C. Ho, Automatic Control Conference, Keynote Address, June 12, 1987.

Y. C. Ho, Math. Theory of Networks and Systems Symposium, Phoenix, AZ, June 15, 1987.

Y. C. Ho, Higher Institute for Electrical and Mechanical Engineering, Sofia, Bulgaria, July 18, 1987.

Y. C. Ho, Academy of Social Science and Administration, Sofia, Bulgaria, July 18, 1987.

Y. C. Ho, Conference on Information Processing in Manufacturing, Dresden, GDR, July 23, 1987.

Y. C. Ho, Tenth World Congress of the International Federation of Automatic Control, Munich, FRG, July 28, 1987.

Y. C. Ho, IIASA Conference on Discrete Event Systems, Vienna/Sopron, Austria/Hungary, August 2, 1987.

Y. C. Ho, ORSA/TIMS National Conference, St. Louis, October 25, 1987.

Y. C. Ho, Rensselaer Polytechnic Institute, November 12, 1987.

Y. C. Ho, IEEE Conference on Decision and Control, Los Angeles, CA, December 9, 1987.

Y. C. Ho, Winter Simulation Conference, Atlanta, GA, December 14, 1987.

David Yao, University of Chicago, January 1987, invited talk.

David Yao, GTE Laboratories, January 1987, invited talk.

David Yao, Northwestern University, January 1987, invited talk.

David Yao, ORSA/TIMS/SIAM Special Interest Meeting on Applied Probability, New Brunswick, January 1987, invited presentations.

David Yao, University of Connecticut, February 1987, invited talk.

David Yao, IEEE Conference on Robotics and Automation, Raleigh, NC, March 1987, paper.

David Yao, ORSA/TIMS Joint National Meeting, New Orleans, May 1987, invited presentations.

David Yao, Bell Communications Research, June 1987, invited talk.

David Yao, Columbia University, Ivy-Plus Symposium on Production, Inventory and Distribution Systems, June 1987, invited talk.

h. Honors/Awards/Prizes

Y. C. Ho was elected to the National Academy of Engineering.

Y. C. Ho served as General Chairman of the 1987 IEEE Robotics and Automation Conference.

Y. C. Ho was elected to the post of President, IEEE Robotic and Automation Council for 1988.

David Yao was given a Presidential Young Investigator Award by NSF.

j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending 1 October 1987

Dr. X. Cao, Dr. R. Conterno, Mr. Y. Dille, Mr. P. Glasserman, Mr. W. Gong, Mr. G. Feigen, Mr. M. Fu, Mr. J. J. Hu, Mr. S. Li, and Mr. P. Vaikili.

IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. T. T. Wu	Mr. M. F. Brown
Prof. R. W. P. King	Mr. N. Filippopoulos
Dr. Y.-J. Mao	Mr. D. K. Freeman (after February 1)
Dr. J. M. Myers	Ms. M. Owens
Dr. H.-M. Shen	Ms. B. H. Sandler
Dr. A. D. Wunsch (until May 31)	

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Application is also made of modeling techniques and the principle of similitude. Most practically significant problems in the area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are concerned primarily with the properties of antennas and arrays and of the electromagnetic fields they generate in various practically important environments that lead to difficult problems with complicated boundary conditions. Examples include dipoles, insulated antennas, traveling-wave antennas and arrays, crossed dipoles, and loops near the boundary between two media such as air and the earth or sea, or the oceanic crust and sea water; the properties of lateral electromagnetic waves; lateral waves and reflected waves in horizontally-layered media;

the generation, propagation, and reception of lateral electromagnetic pulses; arrays of antennas along curved lines; and solitary electromagnetic pulses with slow rates of decay.

IV.1 Analytical and Numerical Determination of the Fields of Antennas near an Interface Between Two Half-Spaces with Significantly Different Wave Numbers. T. T. Wu, R. W. P. King, B. H. Sandler, and M. Owens, Contract N00014-84-K-0465; Research Unit 11.

Electromagnetic surface waves of a type known as *lateral waves* are excited along a boundary between two electrically different half-spaces by both vertical and horizontal electric dipoles located near or on that boundary. Beginning with the papers by Wu and King [1], [2], and King and Wu [3] for the horizontal dipole and by King [4] for the vertical dipole, the general integrals for the components of the electric and magnetic fields were integrated to obtain simple, accurate and continuous formulas valid over radial distances from very close to the source to infinity. These apply specifically to the field in Region 1 and along the boundary in Region 2, subject to the inequality $|k_1| \geq 3|k_2|$ where k_1 and k_2 are the wave numbers of the two half-spaces.

This early work was then extended to include the determination of integrated formulas for the field throughout Region 2 (the half-space in which the lateral wave travels) for both horizontal [5] and vertical [6] electric dipoles located near the boundary in Region 1. The field in Region 2 is shown to include an outward-traveling spherical wave and a lateral wave. The availability of integrated formulas for the field in Region 2 has permitted a detailed study of the properties of the lateral-wave part of the field, including the locus of the Poynting vector, the maximum depth of penetration of the lateral wave into Region 2, and the fraction of power associated with the lateral wave.

During the current reporting period, these results have been further extended

to obtain simple integrated formulas for the complete electromagnetic field (not just the far field) at any point in the air (Region 2) when the dipole is at a height d also in the air [7], [8]. Of particular interest in radio communication over the surface of the earth is the field at any point in Region 2 (air) when the dipole is on the surface of Region 1 (earth or sea). This field is completely and accurately given by the general formulas with $d = 0$. Using the large-argument approximation of the Fresnel-integral terms, simple expressions are also obtained for the complete far field of the unit vertical dipole on the surface of Region 2. Graphs of the magnitude of $E_{2\Theta}(r_0, \Theta)$ for a unit vertical dipole for four different Regions 1 (salt water, lake water, wet earth, dry earth) show that the oscillations in the field patterns due to the interference between the direct field and the field reflected from the imperfectly conducting Region 1 decrease in amplitude with increasing conductivity σ_1 . They disappear when Region 1 is a perfect conductor with $\sigma_1 = \infty$.

References:

1. T. T. Wu and R. W. P. King, "Lateral Waves: A New Formula and Interference Patterns," *Radio Science* **17**, 521-531 (1982).
2. T. T. Wu and R. W. P. King, "Lateral Waves: New Formulas for $E_{1\phi}$ and E_{1z} ," *Radio Science* **17**, 532-538 (1982); Correction, **19**, 1422 (1984).
3. R. W. P. King and T. T. Wu, "Lateral Waves: Formulas for the Magnetic Field," *J. Appl. Phys.* **54**, 507-514 (1983); Erratum, **56**, 3365 (1984).
4. R. W. P. King, "New Formulas for the Electromagnetic Field of a Vertical Electric Dipole in a Dielectric or Conducting Half-Space near its Horizontal Interface," *J. Appl. Phys.* **53**, 8476-8482 (1982); Erratum, **56**, 3366 (1984).
5. R. W. P. King, M. Owens, and T. T. Wu, "Properties of Lateral Electromagnetic Fields and Their Application," *Radio Science* **21**, 13-23 (1986).
6. R. W. P. King, "Properties of the Lateral Electromagnetic Field of a Vertical Dipole and Their Application," *IEEE Trans. Geosci. & Remote Sensing GE-24*, 813-825 (1986).
7. R. W. P. King, "Electromagnetic Surface Waves," invited feature article in *IEEE Antennas and Propagat. Society Newsletter*, **28**, 5-11 (1986).

8. R. W. P. King, "Lateral Electromagnetic Surface Waves and Pulses," invited paper, submitted for presentation at the Heinrich Hertz Symposium, Universität Karlsruhe, FRG, March 14 and 15, 1988.

IV.2 Theoretical Study of Lateral-Wave Propagation in Horizontally-Layered Media. R. W. P. King and T. T. Wu, Contract N00014-84-K-0465; Research Unit 11.

The theoretical work described in the preceding topic is concerned with the electromagnetic field generated by dipoles near the boundary between two homogeneous but electrically different half-spaces. Both half-spaces are assumed to be isotropic, except in the recent study by Pan [1] in which one of the half-spaces is anisotropic in the conductivity with the horizontal values $\sigma_x = \sigma_y$ different from the vertical value σ_z . This is a special form of horizontal layering. In a more general form, one of the half-spaces is composed of a succession of n horizontally bounded layers each with arbitrary thickness and arbitrary wave number. Each layer is homogeneous and isotropic but the wave number is discontinuous across the boundaries. Below the n^{th} layer the rest of the half-space is homogeneous and isotropic to infinity. This layered model is used by geophysicists in the study of the oceanic crust. The general integrals for the electromagnetic field of a dipole in the one homogeneous, isotropic half-space separated from the second such half-space by the n horizontal layers of arbitrary electrical properties have been formulated, and from them simple integrated formulas have been obtained.

These general formulas have then been applied to a layered region with the properties of microstrip [2]. Microstrip can be considered a three-layered region consisting of air-dielectric-conductor. Its properties can be investigated in terms of the electromagnetic field generated by a horizontal electric dipole on the air-dielectric surface—which can be looked upon as an element of a transmission line or antenna—and vertical electric dipoles in the dielectric—which correspond to elements of a vertical conductor joining a horizontal circuit through the substrate to the

conducting plane. The determination of the electromagnetic field in relatively simple form is possible when the following inequalities are satisfied: $k_0^2 < |k_1^2| < |k_2^2|$, where k_j , $j = 0, 1, 2$, are the wave numbers of Region 0 (air), Region 1 (dielectric), and Region 2 (conductor), respectively. Formulas are derived for the tangential electric field along the air-substrate boundary in microstrip and the vertical electric field in its interior when excited by a unit horizontal electric dipole at $\rho = 0$ on the boundary $d = 0$. Although the integrated formulas are simpler and more readily understood than the integrals they approximate, the fields they represent are complicated. Along the boundary, $E_\rho(\rho, \phi, 0)$ and $E_\phi(\rho, \phi, 0)$ each consists of two waves, a lateral wave characterized by the exponential factor $\exp(ik_0\rho)$ that travels in the air with the velocity c and a direct wave characterized by the exponential factor $\exp(ik_1\rho)$ that travels in the dielectric substrate with the velocity $c\epsilon^{-1/2}$. These two components determine the interaction between currents in conductors located on the air-substrate boundary. $E_{1z}(\rho, \phi, z)$ in the substrate also includes a lateral wave that travels along the surface and then down into the substrate and a direct wave that travels directly through the substrate. It determines the coupling between horizontal currents in conductors on the air-substrate boundary and vertical currents in connections from the air surface to the conducting plane. It is noteworthy that, when a dipole operating at a single fixed frequency generates two waves that travel outward with different phase velocities, the effect is similar to—but is not—dispersion. In the case at hand, the permittivities of air and the substrate are assumed to be constants independent of the frequency so that the phase velocities associated with them are also frequency-independent. However, a signal that propagates without dispersion at two different phase velocities is distorted in transmission in a manner similar to that observed with dispersion. If the permittivity of the substrate is frequency-dependent, the part of the signal traveling in it will suffer dispersion, the lateral-wave part in the air will not.

The general formulas derived for n -layered regions have also been applied to a three-layered region consisting of sea water-sediment-oceanic crust. A systematic study has been made of the transverse components E_ρ and E_ϕ on the sea floor in their dependence on the conductivity and thickness of the sediment and the conductivity of the underlying crustal rock. It is found that E_ρ and E_ϕ are both very sensitive to all three parameters and that there is no combination that provides a simultaneously satisfactory fit for both E_ρ and E_ϕ . This is at variance with the calculations of Young and Cox [3] which show a negligible effect on E_ϕ of the properties of 8 layers to a depth of 30 km but a very strong effect on E_ρ . The result suggests again the importance of anisotropy in the uppermost crustal conductivity [1]. The theory for n horizontal layers is also being applied to the case of an eight-layered model used in the study of the conductivity of the oceanic crust and to a three-layered region consisting of air-arctic ice-sea water.

References:

1. W.-Y. Pan, "Surface-Wave Propagation Along the Boundary Between Sea Water and One-Dimensionally Anisotropic Rock," *J. Appl. Phys.* **58**, 3963-3974 (1985).
2. R. W. P. King, "The Propagation of Signals Along a Three-Layered Region: Microstrip," *IEEE Trans. Microw. Theory & Tech.*, submitted for publication.
3. P. D. Young and C. S. Cox, "Electromagnetic Active Source Sounding Near the East Pacific Rise," *Geophys. Res. Lett.* **8**, 1043-1046 (1981).

IV.3 Lateral-Wave Propagation and Modeling of the Lithosphere. M. F. Brown, R. W. P. King, and T. T. Wu, Contracts N00014-79-C-0419 and N00014-84-K-0465; Research Unit 11.

With the direct geophysical utility of the lateral-wave formulas demonstrated [1]-[5], attention has been directed to the study of electromagnetic lateral-wave pulses as possible new tools in geophysical exploration. The study of the observed fine structure of the changes in shape and amplitude of a Gaussian pulse as it trav-

els along a material boundary is in progress. The changes are being parametrized by searching for the best fit (in terms of elementary functions) to the experimental values. The peaked waveforms of highest amplitude have been remeasured to establish repeatability and to construct tables for the parametrization. Several functions have been fitted to the observed values. A correspondence between the specific geophysical influences which elicit distortion and attenuation of the pulse is being sought. The following progress has been made: (a) Using repeated experiments with the pulses radiated from a short *vertical* monopole in air over a dissipative medium, specific correspondences have been made between certain experimental effects and distinct secondary oscillations not formerly understood. For example, oscillations have been identified with the effects of the vertical ground plane, the cabling, and the short finite length of the source antenna [6]. (b) A replacement pair of *horizontal* antennas has been designed and constructed using 316 steel fittings to overcome the corrosion problems evident in earlier models. Pulses generated by these antennas are quite smooth; they are also being parametrized.

The theoretical description of the pulse deformations as a function of the geophysical parameters (conductivity σ and permittivity ϵ), the frequency, and the radial distance is being refined in accord with the observations described above. In particular for a Gaussian pulse, the Wu/King formula for $E_{2z}(\rho, z)$ for the CW mode has been Fourier transformed; the evaluation of the resulting integrals for the conditions of the model tank, antennas, and pulse sources is being pursued using both analytical and numerical techniques. Confluent hypergeometric functions have been used to represent the Fresnel-integral terms [6].

References:

1. M. F. Brown and R. W. P. King, "Shallow Sounding of Crustal Regions Using Electromagnetic Surface Waves," *Radio Science* **21**, 831-844 (1986).

2. R. W. P. King, "Properties of the Lateral Electromagnetic Field of a Vertical Dipole and Their Application," *IEEE Trans. Geosci. & Remote Sensing GE-24*, 813-825 (1986).
3. R. W. P. King, "Electromagnetic Surface Waves," invited feature article in *IEEE Antennas and Propagat. Society Newsletter*, 28, 5-11 (1986).
4. R. W. P. King, "Electromagnetic Surface Waves: New Formulas and Applications," *IEEE Trans. Antennas Propagat. AP-33*, 1204-1212 (1985).
5. R. W. P. King, "Electromagnetic Surface Waves: New Formulas and Their Application to Determine the Electrical Properties Of the Sea Bottom," *J. Appl. Phys.* 58, 3612-3624 (1985).
6. M. F. Brown, "Wave Packets of Lateral Waves Due to a Vertical Monopole: Experiment and Theory," *Radio Science*, accepted for publication.

IV.4 Lateral Electromagnetic Pulses Generated by Horizontal and Vertical Dipoles on the Boundary Between Two Dielectrics. T. T. Wu and R. W. P. King, Contract N00014-84-K-0465; Research Unit 11.

The properties and possible applications of lateral pulses generated by horizontal and vertical electric dipoles on or near the plane boundary between two electrically different media are of considerable interest. Significant progress has been made in the study of lateral-wave pulses excited by current pulses that are delta functions in time. An exact solution in terms of elementary functions has been obtained [1] in the time domain for the vertical electric field $E_z(\rho, t)$ and the transverse magnetic field $B_\phi(\rho, t)$ of a dipole located on the plane boundary $z = 0$ between air (Region 2, $z < 0$) and a perfect dielectric (Region 1, $z > 0$) when the dipole is excited by a single delta-function current pulse. The vertical electric field on the boundary consists of two delta-function pulses that travel with the velocities c and $c\epsilon^{-1/2}$ and arrive at the times $t - \rho/c$ and $t - \rho\epsilon^{1/2}/c$. The first pulse travels in the air, the second in the dielectric. Both pulses have the amplitude factor ρ^{-2} . Thus, the transient field at *all radial distances* has the same radial dependence as the far field along the boundary in the steady state. The field varies in a complicated manner in the interval between the two pulses with a radial dependence of

$\rho^{-1/2}$. After the second pulse has passed, the electric field drops to a final static value due to the oppositely charged ends of the dipole. The horizontal magnetic field is similar, except that it drops abruptly to zero after the second pulse has passed. For comparison, the vertical electric field in the equatorial plane of the same dipole in a homogeneous dielectric has also been derived. The comparison indicates that the field along the boundary is a surface-wave or lateral pulse. Instead of a $1/\rho$ amplitude factor which is characteristic of propagation in an unbounded region, the amplitude factor of the pulsed field along the boundary is $1/\rho^2$ which is characteristic of the surface wave.

The exact evaluation of the transient field by the Fourier transformation of the general integrals has been achieved only for the components B_ϕ and E_z generated by a delta-function current in a vertical dipole on the boundary between two dielectrics [1]. These components have subsequently been reevaluated [2], [3] from the approximate, relatively simple forms previously available for the frequency domain, subject to the inequalities $|k_1|^2 \geq 9|k_2|^2$, $|k_1\rho| \geq 3|k_2\rho| \geq 3$. For dielectrics with $k_1 = k_2\epsilon^{1/2}$, $k_2 = \omega/c$, $\epsilon_{2r} = 1$, and $\epsilon_{1r} = \epsilon$, these inequalities include $\epsilon \geq 9$. The significance of this condition in the time domain is of interest. Note that $\epsilon \geq 9$ means that, in the derivation of the steady-state formulas, terms that are of the order ϵ^{-1} have been neglected by omission where convenient. Because of this approximation the second pulse $\delta(t - \rho\epsilon^{1/2}/c)$ is absent in the approximate formulas. The ratio of its amplitude coefficient to that of the first pulse $\delta(t - \rho/c)$ is ϵ^{-2} or $\epsilon^{-3/2}$, both of which are very small when $\epsilon \geq 9$. A numerical calculation of the exact and approximate formulas for $B_{2\phi}$ and E_{2z} in the range $\rho/c < t < \rho\epsilon^{1/2}/c$ between the two pulses has been tabulated for two values of ϵ . The comparison shows quite remarkable agreement between the two superficially quite different formulas.

Since the approximate formulas are excellent approximations for B_ϕ and E_z , they have also been used to evaluate E_ρ for the vertical dipole and all six of the

more complicated components of the horizontal electric dipole. This approximate approach has also been used to evaluate the transient field when the dipole is excited by a Gaussian pulse [2], [3]. As with the delta-function pulse, the omission of small terms with magnitudes smaller than ϵ^{-1} in the frequency-domain formulas must lead to the nonappearance of a second pulse whose amplitude is very much smaller than the first pulse because it is multiplied by a factor of the order ϵ^{-2} . The approximate formulas can be expected to be quite accurate before the second pulse arrives and to give the correct final static values. The vertical electric field has been plotted as a function of time for seven different radial distances. The shape of the pulse is determined by the relative contributions from the four terms appearing in the final formula for $E_{2z}(\rho, t)$ with their very different dependences on the radial distance and the time. The third term represents the rapid increase in the vertical electric field as the pulse passes and leaves the final electrostatic field of the charged infinitesimal dipole. This part of the field decreases as $1/\rho^3$ with distance. The second term is a Gaussian pulse that travels with the phase velocity c and with a decrease in amplitude of $1/\rho^2$. The first term is the time derivative of the Gaussian pulse; it decreases with distance only as $1/\rho$ so that it persists for much greater distances than does the $1/\rho^2$ term. Unlike the field with the delta-function pulse or the steady-state field, the fourth term due to the Fresnel integral does not completely cancel the $1/\rho$ term. Its behavior is similar to a negative derivative of the Gaussian pulse. Since the $1/\rho$ term is not completely cancelled by the Fresnel-integral term, it may be presumed that the Gaussian pulse decreases more slowly in amplitude with increasing radial distances than the steady-state field. The degree of cancellation of the $1/\rho$ term must increase as the pulse width is made smaller, decrease as it is made larger. That is, the greater the low-frequency content of the Gaussian pulse, the slower is its decrease in amplitude at large radial distances.

References:

1. T. T. Wu and R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on the Boundary Between Two Dielectrics," *J. Appl. Phys.*, accepted for publication.
2. R. W. P. King, "Lateral Electromagnetic Surface Waves and Pulses," invited paper, submitted for presentation at the Heinrich Hertz Symposium, Universität Karlsruhe, FRG, March 14 and 15, 1988.
3. R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on a Plane Boundary Between Dielectrics," *Journal of Electromagnetic Waves and Applications*, invited paper, submitted for publication.

IV.5 Lateral Electromagnetic Waves (Manuscript for Book). R. W. P. King, T. T. Wu, M. Owens, and B. H. Sandler, Contracts N00014-84-K-0465 and N00014-79-C-0419; Research Unit 11.

It has become a tradition in the publication of researches in the area of electromagnetic phenomena to periodically summarize and coordinate major segments in book form. Accordingly, a manuscript is in preparation which contains the results of current and past researches on lateral electromagnetic waves that have been supported by the above JSEP and ONR Contracts. The chapter headings are: 1. Introduction to Lateral Waves, 2. Electromagnetic Preliminaries, 3. The Electromagnetic Field of a Vertical Dipole in the Presence of a Plane Boundary, 4. Applications of the Theory of the Vertical Dipole near The Boundary Between Two Half-Spaces, 5. The Electromagnetic Field of a Horizontal Electric Dipole in the Presence of a Plane Boundary, 6. Interference Patterns; Comparison of Approximate Formulas with General Integrals and Measurements, 7. Applications of the Theory of the Horizontal Dipole near the Boundary Between Air and Earth or Sea, 8. The Measurement of the Conductivity of the Oceanic Lithosphere with a Horizontal Antenna as the Source, 9. Lateral Waves in a One-Dimensionally Anisotropic Half-Space, 10. The Propagation of Lateral Electromagnetic Waves in Air over Vertical Discontinuities, 11. The Horizontally Layered Half-Space, 12. The Three-Layer Problem for Sediment on the Oceanic Crust, 13. The Propagation of Signals Along

a Three-Layered Region: Microstrip, 14. Lateral Electromagnetic Pulses Generated by Vertical Dipoles, 15. Approximate Formulas for Lateral Electromagnetic Pulses Generated by Vertical and Horizontal Electric Dipoles, 16. Antennas in Material Media Near Boundaries: The Bare Metal Dipole, 17. Antennas in Material Media Near Boundaries: The Terminated Insulated Antenna, 18. The Wave Antenna.

IV.6 Fields and Currents and Charges on Obstacles in a Parallel-Plate Simulator at Selected Frequencies and with Pulse Excitation.

H.-M. Shen, R. W. P. King, and T. T. Wu, Contract N00014-84-K-0465; Research Unit 11.

The extensive series of theoretical and experimental investigations of the properties of EMP simulators that has been carried out at Harvard over the past ten years has been concluded with a study [1] to clarify the performance of each section of the parallel-plate simulator in forming the electromagnetic pulse (EMP) in the parallel-plate section or working volume of the simulator. All previous analyses of the parallel-plate simulator system have shared the assumption that the parallel plate is important in forming the EMP because the working volume is inside the parallel-plate region. The experimental and theoretical study conducted at Harvard of the rhombic wire simulator under pulse excitation [2], [3] showed, in contrast, that the EMP in the working volume is excited by the current in the wires near the source rather than the current in the wires near the center. This is referred to as "source region excitation" or SRE. This observation is somewhat different from the situation in the frequency domain. In order to determine whether a similar situation exists for the parallel-plate simulator, an analysis of the subpulses emitted from subregions of the sloping triangular and parallel rectangular plates has been undertaken. The analysis shows that the three sections of the parallel-plate simulator play quite different roles in forming the EMP in the working volume. When the length of the parallel-plate section is close to the height between the two parallel

plates (which is true in most practical cases), the simulator is essentially a cone-plate radiator rather than a parallel-plate waveguide. The EMP in the working volume is contributed by the current pulses on the triangular plate near the pulse generator, so that the parallel plate actually plays a rather small role in forming the EMP in the working volume. The main role of the middle and rear plates is to guide the current pulse to the terminal to avoid reflection. It can be constructed in many different ways without affecting the EMP in the working volume.

References:

1. H.-M. Shen, R. W. P. King, and T. T. Wu, "The Exciting Mechanism of the Parallel-Plate EMP Simulator," *IEEE Trans. Electromagn. Compatibil.* EMC-29, 32-39 (1987).
2. H.-M. Shen, R. W. P. King, and T. T. Wu, "An Experimental Investigation of the Rhombic EMP Simulator under Pulse Excitation," *IEEE Trans. Electromagn. Compatibil.* EMC-25, 40-46 (1983).
3. H.-M. Shen, R. W. P. King, and T. T. Wu, "Theoretical Analysis of the Rhombic Simulator under Pulse Excitation," *IEEE Trans. Electromagn. Compatibil.* EMC-25, 47-55 (1983).

IV.7 Theoretical Study of Electromagnetic Pulses with a Slow Rate of Decay. T. T. Wu, R. W. P. King, J. M. Myers, and H. M. Shen, Contracts N00014-84-K-0465, Army LABCOM DAAL02-86-K-0095, and DOE Grant DE-FG02-84ER40158; Research Unit 11.

The interesting possibility of generating electromagnetic pulses which propagate in a manner such that the energy associated with them decreases with distance R much more slowly than as R^{-2} is being investigated. It was shown earlier [1] that theoretically the decrease in the energy of a pulse, unlike that of a CW signal, need not be of the form R^{-2} but can instead be arbitrarily slow. Such cases of slow decrease are referred to as electromagnetic missiles. Two examples of an electromagnetic missile were known at that time [1], each involving a current distribution in a plane.

During the current reporting period, efforts have been directed toward determining the general characteristics of the distributions of current and charge that generate these slowly decaying pulses. The analyses demonstrate that electromagnetic missiles are of rather common occurrence provided the pulse excitation has a special fast-rising shape. This result turns out to be the criterion of an electromagnetic missile or the *electromagnetic-missile condition*. Using this criterion, it has been found that electromagnetic missiles can be launched from a surface source, a line source, or a point source. For each of these three types of source, a particular configuration has been studied. These are described in sequence below.

The simplest idealized aperture antenna that can launch an electromagnetic missile is an open-ended, ideally semi-infinite, circular waveguide excited in the distribution characteristic of the lowest transverse mode, the TE_{11} mode. The formal solutions for the currents using the Wiener-Hopf technique for TE_{0n} modes have been obtained and, from them, the integral solution of the radiation fields has been derived. In order to evaluate this integral, the singularities and asymptotic behavior of the integrands in the integral have been studied in detail. Work is currently in progress to derive a formal general solution for the transient case of radiation for an arbitrary time function of the electric field on the axis (or its derivative) by superimposing the single-frequency solutions. Preliminary results show that the open circular waveguide excited by a TE_{11} -mode pulse can launch an electromagnetic missile.

The second configuration investigated is the circular cylindrical lens excited by a line source [2]. The possibility of launching an electromagnetic missile from a line source within a cylindrical lens is studied initially in terms of optical ray tracing. The precise series solution for the radiation field in the frequency domain is then obtained from the Helmholtz equations and the boundary conditions. After using the asymptotic expansion for unlimited frequency, the radiation in the far

region is found to be characterized by electromagnetic-missile effects, provided the index of refraction and the location of the linear source satisfy certain relations.

The final structure studied to date is the uniform dielectric sphere under transient excitation by a point source [3], [4]. It too is capable of launching an electromagnetic missile under suitable conditions involving the index of refraction, the radius of the sphere, and the location of the point source. The condition for the presence of an electromagnetic missile is found to have a natural interpretation in the language of optics. In the case without rotational symmetry, the electromagnetic-missile condition is generalized to the vanishing of the Jacobian, viz., $\partial\Omega/\partial\Omega_0 = 0$, where Ω and Ω_0 are both points on a unit sphere and $\Omega_0 \rightarrow \Omega$ is a mapping of the unit sphere into itself. This is related to the well-known mathematical concept of singularities of differential maps in two dimensions. Thus, the condition can be stated as follows: With a suitably chosen point source, an electromagnetic missile can be generated in the direction Ω if and only if Ω is a critical point of the two-dimensional differentiable mapping $\Omega_0 \rightarrow \Omega$. This leads to the classification of electromagnetic missiles as follows: (A) Critical points that change qualitatively if the mapping is perturbed, or (B) Critical points that do not change qualitatively if the mapping is perturbed. Electromagnetic missiles of Type A are in general stronger. The most interesting example is the case where the critical point is an isolated point. In this case, the decay of the electromagnetic missile can be as slow as one wishes, with a suitable choice of the time dependence of the point source. Examples of an isolated critical point include the two examples of ref. 1, the spherical lens, the paraboloidal reflector with the point source at the focus, and the prolate spheroidal lens. Electromagnetic missiles of Type B can be further classified using Whitney's theorem. There are two distinct cases: (B1) The critical point is a Whitney fold, and (B2) The critical point is a Whitney pleat. In the first case, that of a Whitney fold, the decay of the electromagnetic missile must be

faster than R^{-1} but slower than R^{-2} . In other words, the electromagnetic missile is relatively weak. The interesting case of the Whitney pleat will be treated in a future paper.

In the investigation of the spherical lens it was found that reflected rays can also lead to electromagnetic missiles. This generalization is being studied further. A general analysis is being carried out of the internal multiply-reflected radiation field when the point source is either inside or outside the dielectric sphere. A precise solution similar to that obtained for the directly transmitted ray is being sought.

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3. T. T. Wu, R. W. P. King, and H.-M. Shen, "The Spherical Lens as a Launcher of Electromagnetic Missiles," *J. Appl. Phys.*, accepted for publication.
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IV.8 Experimental Study of Electromagnetic Pulses with a Slow Rate of Decay.

T. T. Wu, R. W. P. King, J. M. Myers, and H. M. Shen, Contracts N00014-84-K-0465 and Army LABC0M DAAL02-86-K-0095; Research Unit 11.

An experimental investigation to design a prototype pulse launcher of electromagnetic missiles is in progress. The development of suitable electromagnetic transient fields requires the more-or-less fixed setup described below along with a cut-and-try approach to making a workable antenna structure to combine with commercially available pulse generators. The fixed setup consists primarily of a horizontal 51' by 16' metal ground plane with a parabolic dish mounted at one end.

The purpose of the conducting ground plane is to allow a transient field polarized vertically in that plane to propagate in the half-space above the plane as if it were propagating in free space. The crawl space under the ground plane can be used for inserting measurement probes to measure the field without the problem of the cabling for these probes affecting the field. The ground plane has been constructed, each of its aluminum plates has been connected by electrically conductive, pressure-sensitive tape, and absorbing material has been placed along the walls on all sides of the ground plane. A parabolic dish has been purchased and incorporated into the ground plane. Other equipment purchased for this setup include a 60-picosecond pulse generator, and a Tektronix Model 7854 sampling oscilloscope. The various pieces of measuring equipment have been tested.

Initial measurements of the electric field emitted directly from the feeding monopole antenna located at the focus of the parabolic dish produced waveforms of the electric field that were attenuated oscillations rather than single pulses. The oscillations were found to be due in part to the resonance of the receiving antenna, a small cylindrical monopole, and in part to the frequency response of the cables and other accessories. These results suggested the need to change the sensors to wider-band conical monopoles and to replace the BNC-series connectors and cables (0–4 GHz) with SMA-series (0–15 GHz). Because these first measured pulse signals were rather weak, a higher-output voltage pulse generator was deemed necessary and a Picosecond Model 4000C pulse generator with four-times the output has been ordered.

Changing the receiving antenna from a cylindrical monopole to a wider-band conical monopole considerably reduced the amount of oscillation in the observed signal. Nevertheless, a small attenuated oscillation remained. The solution to this problem was then found by using an L-antenna as the receiving sensor. This permitted a nearly perfect acquisition of the electric field. The waveform from the

L-antenna at this stage showed almost the same rise time as that directly from the pulse generator, with no oscillation, and only slight distortion. The width of the pulse was increased by 20 ps and the tail of the pulse was different from that of the original source pulse. The following approaches were then taken to reduce the distortion even further: A sampling head extender was added; this has reduced the width of the recorded pulses by 20%. The vertical length of the receiving L-antenna was shortened to less than 10 mm; this has reduced the pulse width to less than 60 ps. Lastly, the cylindrical monopole antenna being used as the transmitter has been replaced by a new V-conical antenna; this has improved the rear part of the pulse. As a result of these alterations, the distortion in the waveform of the radiated electromagnetic field has been virtually eliminated. The difference in the width is now less than 5 ps. The rear parts of the two pulses coincide except for the tail, which is due to the reflection from the end of the V-conical antenna. More accurate measurements of the electric field along the z -axis on the ground plane are now possible.

Recent measurements along the z -axis on the ground plane show that the waveforms of the electric field are very complicated pulse sequences. They consist of a primary subsequence of pulses emitted directly from the monopole at the focus point and a secondary subsequence of pulses reflected from the dish. The origin of each of the pulses within the two pulse subsequences has been identified. The manner in which the two pulse subsequences decrease is totally different. The primary subsequence decreases according to $1/z$, whereas the secondary subsequence decreases much more slowly. Within the first 20 feet, its amplitude remains constant and then decreases very slowly. When the distance reaches 49 feet, the amplitude of the secondary subsequence is 60% of its initial value, while the amplitude of the primary subsequence is only 7%.

IV.9 Superdirective Properties of Closed Loops of Parallel Coplanar Dipoles. T. T. Wu, R. W. P. King, N. Filippopoulos, and D. K. Freeman, Contract N00014-84-K-0465 and DOE Grant DE-FG02-84ER40158; Research Unit 11.

After the needlepoint radiation pattern of Einstein [1] was proved theoretically possible early in this century [2], the quest for a supergain antenna with such a pattern was pursued intermittently with largely negative results. A recent investigation in quantum mechanics [3] has propelled the Yagi array with many parallel dipole elements arranged in a closed loop into the spotlight as a prospective superdirective antenna. A review of the properties of the Yagi and circular arrays of dipoles driven by one element has confirmed the existence of the predicted resonances and exceedingly low losses. A superdirective antenna with a needlepoint radiation pattern is a highly advanced antenna concept, the realization of which would advance basic knowledge of electromagnetic radiation and be of great importance in point-to-point and satellite communication, radar, and space warfare. A systematic investigation to study and reduce to practice the superdirective properties of closed loops of coplanar dipoles has been initiated. Advanced analytical, numerical, and experimental techniques will be used to design such an antenna and construct a working model. The research will begin with a precise phase-sequence analysis of a circular array of up to 150 dipoles and the computer-aided calculation of the crucial mutual admittances, distributions of current, and overall resonances. Concurrently, provided additional financial support is obtained, an experimental array of 48 elements will be constructed on a large existing ground screen with a design that permits tuning to resonance. Calculated and measured results when available will be used to obtain an optimum design for the circular array. The next step is to extend the design criteria to elliptical and egg-shaped arrays with superdirective field patterns. The final step may be to supercool the array to eliminate ohmic losses and enhance the Q and the directive gain.

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**ANNUAL REPORT OF
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

a. Papers Submitted to Refereed Journals (and not yet published)

M. F. Brown, "Wave Packets of Lateral Waves Due to a Vertical Monopole: Experiment and Theory," *Radio Science*, accepted. (Partial support from ONR Contract N00014-79-C-0419.)

T. T. Wu and R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on the Boundary Between Two Dielectrics," *J. Appl. Phys.*, accepted.

T. T. Wu, R. W. P. King, and H.-M. Shen, "The Spherical Lens as a Launcher of Electromagnetic Missiles," *J. Appl. Phys.*, accepted. (Partial support from Army LABCOT Contract DAAL02-86-K-0095.)

R. W. P. King, "Lateral Electromagnetic Pulses Generated by a Vertical Dipole on a Plane Boundary Between Dielectrics," *Journal of Electromagnetic Waves and Applications*, invited.

R. W. P. King, "Lateral Electromagnetic Surface Waves and Pulses," *Heinrich Hertz Symposium*, Universität Karlsruhe, FRG, March 14 and 15, 1988, invited.

R. W. P. King, "The Propagation of Signals Along a Three-Layered Region: Microstrip," *IEEE Trans. Microw. Theory & Tech.*

T. T. Wu, R. W. P. King, and H.-M. Shen, "Circular Cylindrical Lens as a Line-Source Electromagnetic-Missile Launcher," *IEEE Trans. Antennas Propagat.* (Partial support from Army LABCOT Contract DAAL02-86-K-0095.)

b. Papers Published in Refereed Journals

R. W. P. King, "Properties of the Lateral Electromagnetic Field of a Vertical Dipole and Their Application," *IEEE Trans. Geosci. & Remote Sensing GE-24*, 813-825 (1986).

R. W. P. King, "Electromagnetic Surface Waves," invited feature article in *IEEE Antennas and Propagat. Society Newsletter*, 28, 5-11 (1986).

H.-M. Shen, R. W. P. King, and T. T. Wu, "The Exciting Mechanism of the Parallel-Plate EMP Simulator," *IEEE Trans. Electromagn. Compatibil. EMC-29*, 32-39 (1987).

A. Grossmann and T. T. Wu, "A Class of Potentials with Extremely Narrow Resonances," *Chinese Journal of Physics* 25, Special Issue in Commemoration of Professor Wu Ta-You's Eightieth Birthday, 129-139 (1987). (Partial support from DOE Grant DE-FG02-84ER40158.)

h. Contributed Presentations at Topical or Scientific/Technical Society Conferences

T. T. Wu and H.-M. Shen, "Developmental Study of Electromagnetic Missiles," URSI Radio Science Meeting (Commission B), Virginia Polytechnic Institute, Blacksburg, VA, June 1987. (Partial support from Army LABCOT Contract DAAL02-86-K-0095.)

i. Honors/Awards/Prizes

R. W. P. King, The Harold Pender Award for 1986, awarded by the Faculty of the Moore School of Electrical Engineering of the University of Pennsylvania, Philadelphia, PA, October 1986.

j. Graduate Students and Postdoctorals Supported under the JSEP for the Year Ending 1 October 1987

Dr. Y.-J. Mao, Dr. A. D. Wunsch, and Mr. N. Filippopoulos.

V. SIGNIFICANT ACCOMPLISHMENTS REPORT

V.1 From the Semiclassical to the Quantum Regime in the Josephson Effect. M. Tinkham, M. Iansiti, A. T. Johnson, and C. J. Lobb; Research Unit 4, SOLID STATE ELECTRONICS.

Ever since the development (in 1950) of the Ginzburg-Landau theory of superconductivity, in which a macroscopic wavefunction $\psi(r)$ was introduced to describe the superconducting condensate, it has been customary to attribute the phenomena of superconductivity to the properties of this macroscopic quantum state. In fact, this is a mean-field theory, in which $\psi(r)$ is treated as a *semiclassical* field in which both the magnitude of ψ and its phase φ have precisely defined values at each point in space with zero uncertainty. In the specific case of a Josephson junction, the semiclassical approximation ignores the fact that the phase φ and the number of Cooper pairs transferred by tunneling are noncommuting quantities, so that it is incompatible with the quantum uncertainty relation

$$\Delta\varphi\Delta N \geq 1$$

for both N and φ simultaneously to have sharply defined values. In conventional Josephson junctions with large capacitance, this semiclassical approximation is justified because the charging energy associated with the transfer of pairs $\sim (\Delta N)^2(2e)^2/2C$ is very small compared with the Josephson coupling energy $E_J = \hbar I_c/2e$. This allows a state to be constructed out of a sufficient range of ΔN to permit $\Delta\varphi \ll 1$, without significant energy cost. In the lowest energy state, one finds specifically that $\Delta\varphi \sim (E_c/E_J)^{1/4}$, where the one-electron charging energy $E_c = e^2/2C$. Thus, $\Delta\varphi \rightarrow 0$ as $(I_c C) \rightarrow \infty$, and the semiclassical approximation is justified for junctions with large C and/or large I_c (or, equivalently, small R_n).

Recently, there has been an increase of interest in junctions which do not fit into this semiclassical regime, but show true quantum effects of a higher order. A well-known example is the work on macroscopic quantum tunneling (MQT), in which the phase variable occasionally tunnels through the potential barrier $E_J \cos \varphi$ to escape to the finite voltage state, in which the phase is freely running. This process is analogous to the escape of an alpha particle from a radioactive nucleus by quantum tunneling, but now involving a *macroscopic* variable φ instead of the coordinate of a single α -particle. A characteristic difference in the macroscopic case is the important role played by damping processes in reducing the tunneling rate. Although the tunneling process is intrinsically quantum mechanical, the description of the phase before and after tunneling is still basically a semiclassical one, since the junctions used have quite large values of C and I_c .

With the development of our microfabrication techniques, we have now succeeded in making very small junctions with capacitance $\sim 1 \text{ fF}$ (femtofarad = 10^{15} F), and normal resistances as large as 10^5 ohms. In such junctions the charging energy E_c is larger than E_J and kT , and the phase variable becomes so delocalized on the scale of 2π that the semiclassical description with a well-defined phase value is simply inadequate. Rather, tunneling from one minimum of the cosine potential to the next occurs continuously, and an extended wavefunction and energy band model may become a better description of the state of the junction. The presence of damping reduces the tunneling rate below the simple estimates made using nondissipative conventional quantum theory, however, affecting the results to an important and perhaps decisive degree. The operational evidence for these new quantum effects is that the measured critical current as $T \rightarrow 0$ is an order of magnitude smaller than it would be in a semiclassical junction with the same normal resistance, and scales with R_n^{-2} rather than R_n^{-1} as it would be in the semiclassical case. In addition, there is a measurable resistance even below I_c .

which we attribute (at $T \rightarrow 0$) to the continuously-occurring quantum tunneling.

A more complete technical description of the work in our laboratory, the results of which are summarized here, may be found in the body of this Annual Report, under Research Unit #4.

V.2 Perturbation Analysis (PA) of Discrete Event Dynamic Systems (DEDS). Y.C. Ho; Research Unit 10, INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION.

Perturbation Analysis (PA) of Discrete Event Dynamic Systems (DEDS) is a technique for the efficient estimation of performance sensitivity with respect to system parameters. As such it is most useful for the design and optimization of such systems. PA was accidentally discovered as an *ad hoc* by-product to the solution of a specific production line management problem in 1978. The first breakthrough came in 1981 when it was experimentally demonstrated that PA can be applied to more general queueing networks. However, like all radically new ideas in science, it was the source of much controversy and disbelief. Rigorously provable results lagged behind experimental evidences of its general applicability. The year 1986-87 represents a watershed in the development of PA techniques. Major breakthroughs in the theoretical foundation of PA were accomplished which firmly established PA as a general approach to the analysis of DEDS. The smoothed PA technique and the extended PA technique reported in this annual report are two key extensions which permit the application of PA to situations heretofore thought to be beyond its capability. More importantly, PA presents a complementary mind set to the traditional probabilistic approach for the treatment of DEDS. We foresee many examples of fruitful synergism in years to come.

V.3 Lateral Electromagnetic Pulses. T. T. Wu, R. W. P. King, and M. F. Brown; Research Unit 11, ELECTROMAGNETIC PHENOMENA.

Continuous lateral electromagnetic waves have been shown to have unusual properties [1] that make them useful for the remote sensing of buried or submerged objects [2], [3], the exploration of the oceanic crust in a shallow layer below the sea floor [4], [5], and communication with submerged submarines [6]. A potentially powerful supplement or alternative to continuous waves is the single pulse or wave packet which could add a new dimension to remote sensing and geophysical exploration.

How are lateral electromagnetic pulses generated? How do they propagate? What are their properties and how can these be used? Significant progress has been made both theoretically and experimentally in providing answers to these basic questions. The following major contributions can be listed:

(1) The exact solution has been obtained for the time-dependent vertical electric and horizontal magnetic fields generated by a vertical electric dipole on the boundary between two electrically different dielectrics, like air and lake water, when the dipole is excited by a delta-function current pulse [7]. This field consists of lateral electromagnetic pulses. (2) Approximate solutions have been obtained for the complete electromagnetic field generated by delta-function and Gaussian current pulses in vertical and horizontal electric dipoles on or near the boundary between two electrically different dielectrics [8]. A comparison with the two exact components obtained under (1) provides a check on the range of validity of the approximate formulas. An extension to include the boundary between one perfect and one imperfect dielectric has also been made [9]. (3) Vertical and horizontal antennas have been designed and tested in a model tank. These generate lateral electromagnetic

pulses with approximate Gaussian shape. They have been observed and measured along the boundary surface [9].

New tools in the form of lateral electromagnetic pulses have been made available for further study and useful application.

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